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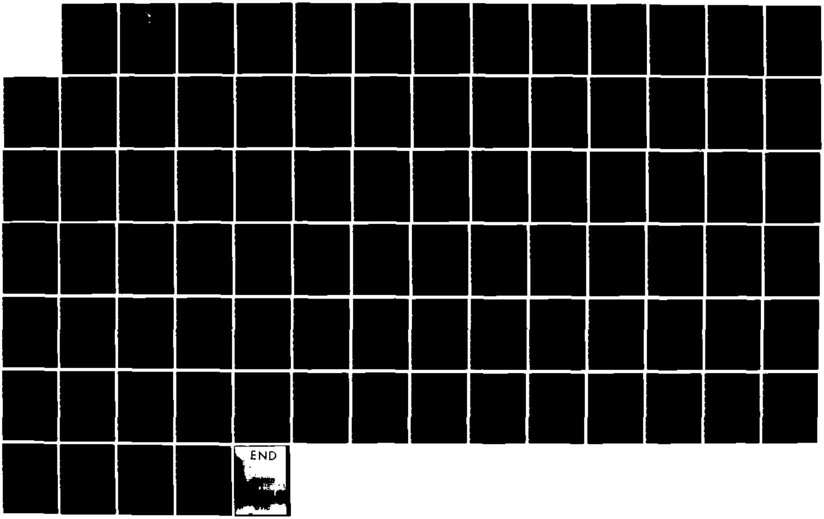

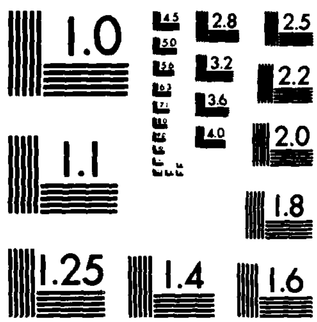

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INVESTIGATION OF MULTIPLE CONTROLLER SYSTEM EFFICIENCY AS APPLIED TO THE CSDLI MODEL

THESIS

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First Lieutenant, USAF

AFIT/GA/AA/84M-2

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

Robert G. Baker

1st Lt, USAF

Graduate Astronautical Engineering

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PREFACE

Few individual projects that require substantial amounts of time and effort are completed without the help of others. I wish to thank several who have given large contributions to this effort.

To my thesis Advisor, Dr. R.A. Calico, I am thankful for your support and guidance as I learned my way through this topic. I hope the findings of this investigation may be of use to you.

To my wife, Janet, and my daughter, Faith, thank you for your love, support, and understanding through some very difficult times. I pray that you, too, may reap some benefit from your contributions to this study.

Finally, I want to thank my Lord and Savior, Jesus Christ, who is responsible for any abilities that I might have.

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ABSTRACT

Modern optimal control methods are used to develop a three controller system. The control problem is formulated in state vector form using full state feedback. The control is implemented on a modal representation of the structural equations of motion. State estimates are provided by a deterministic observer. A computer model is used to generate controller and estimator gains using steady state optimal regulator theory. Means for extracting structural response and control effort time histories are developed and related to the computer model.

The three controller system is used to control the CSDLI model subjected to physical initial conditions. This model is a lumped mass tetrahedral truss consisting of four unit masses that are pin-connected by massless rods. Two versions of the model are used: The nominal version as designed by the Draper Lab and a perturbed version designed to minimize the deflection due to a static load.

Four structure/controller configurations are tested via computer simulations. Compatibility of modal groupings and the use or non-use of system triangularization are the factors varied to form the controller configurations. All configurations use three controllers each controlling four of the twelve modes. Modal input to the program is supplied by a NASTRAN analysis of each structure. Time histories of structural response and expended control effort are computed for each test configuration using a series of structural response weightings to vary the control and estimator gains. Performance curves are formed for each configuration to allow comparison of system efficiencies. The effect of the separate combination of modal compatibility and use or non-use of system triangularization on system efficiency is examined. The relative "controllability" of the two structures is also discussed.

INVESTIGATION OF MULTIPLE CONTROLLER
SYSTEM EFFICIENCY AS APPLIED TO THE CSDLI MODEL

I. INTRODUCTION

Current successes and projected developments in the space transportation system point to the possibility of construction in space of structural systems not now possible. These large space structures (LSS) may be too large to transport and too flexible to withstand earth's higher gravity environment. The projected spans of these systems range from hundreds to thousands of feet. Long, lightweight members and trusses make such extremely large structures possible, but also make them very flexible. This added flexibility takes the form of an increased number of lower frequency vibrational modes. Many of these low frequency modes will fall within the bandwidth of the control system and thus require active control.

As the number of modes that must be included in the control model increases, limits in on-line computing speed and off-line computing accuracy force the use of multiple controller systems. These systems are comprised of a number of independent controllers each controlling a subset of the controlled modes. The number of modes that such systems can handle seems limited only by the expense and weight of the extra hardware and by the ability to design stable systems. Miller, Calico and Miller, and Aldridge (Refs 1-3) have demonstrated multiple controller design techniques that guarantee overall system stability.

As larger, more flexible structures force active control of increasing numbers of modes, the increased amount of energy required to control the system becomes a factor worthy of consideration. Since added energy requirements mean additional fuel, electrical sources, or solar cell area, the problems of large size and flexibility could be further compounded.

As these large space structures become reality, so will the need to design the most efficient structure/control system configuration possible. Current structures research emphasizes redesign techniques that perturb a baseline design to yield a "more controllable" structure. Since much of the structural geometry and placements of lumped masses on a structure may be predetermined, most of these methods deal with techniques for determining stiffness changes. Design methods of possible use include those that produce structures designed for separation of natural frequencies, minimum deflection under a static load, advantageous modal characteristics and structural approximation of the optimal regulator control solution. Because structural mass is always a consideration in evaluating systems intended for use in space, most of these techniques form redesigns holding the total mass (or equivalently, the total stiffness) constant. It is likely that the most advantageous design technique for a particular system will depend on the performance criteria used to evaluate the structural response.

Proper comparison of structural designs, or in general, structural design techniques, requires that the most efficient control system possible be applied to each structure tested. This could easily require a different controller configuration for each structure or technique compared. Much additional study is needed to adequately understand the factors involved in configuring efficient multiple controller systems. These studies will require a computer model capable of forming multiple controller systems and simulating the response of the control system as well as the structural response. The controller configuration must be very flexible, and the simulations should be capable of providing any data desired. Aldridge (Ref 3) developed a computer program using the logical

structure presented by Miller (Ref 1) that is capable of forming a three or four controller system. The program can also decouple the controllers to form a decentralized control system by eliminating the combination of observation and control spillover necessary to block triangularize the closed loop system matrix.

The intent of this thesis is to investigate the effects of two control configuration factors on multiple controller system efficiency. A modified version of Aldridge's program will be used to form three-controller systems for the controller configurations of interest. These control systems will be applied to the CSDLI model subject to a set of initial conditions. The applicability of this model to studies of large space structure control problems has been well demonstrated. Line of sight pointing accuracy is used as the criterion of system performance. Control system performance and efficiency will be evaluated by time histories of structural response and total expended control effort. The controllers designed use position sensors and a deterministic observer to estimate modal amplitudes and point force actuators to implement the control.

The following sections detail the CSDLI model, the computer program with the modifications used to form the controller response, and the investigation to be undertaken. Following the discussion of the investigation, the results, conclusions and recommendations are presented.

II. TEST MODEL

The demonstration and validation of structural design and controller design techniques for large space structures is a difficult task. By nature, large space structures are not readily categorized by a few simple examples. This is largely due to the widely varied forms of large space structures and the large number of structural vibration modes which must be considered in modelling them. In response to the need for a simple test example, the Charles Stack Draper Laboratory (CSDL), Inc., of Cambridge Massachusetts, developed two conceptual structural models. The first of these is a lumped mass tetrahedral truss referred to as the CSDLI model. The second model, CSDLII, is a larger order generic optical space platform. Only the tetrahedron model will be used in this investigation. The following presents the CSDLI model and its pertinent characteristics.

CSDLI Model

The CSDLI model was selected for its simplicity, low order, and similarity to basic large space structures from both a structures and a controls point of view. Because this model has only four nodes which are allowed to move the visualization of time responses in physical coordinates is quite simple. This structure provides a low order model to which control systems are easily applied. Low order also allows all modes to be both modelled and actively controlled. This simplifies verification of the computer model and reduces uncertainties in the results when the investigation is focused on structural design rather than design of the control system. Also, the response characteristics of this model are very similar to those observed in large space structures.

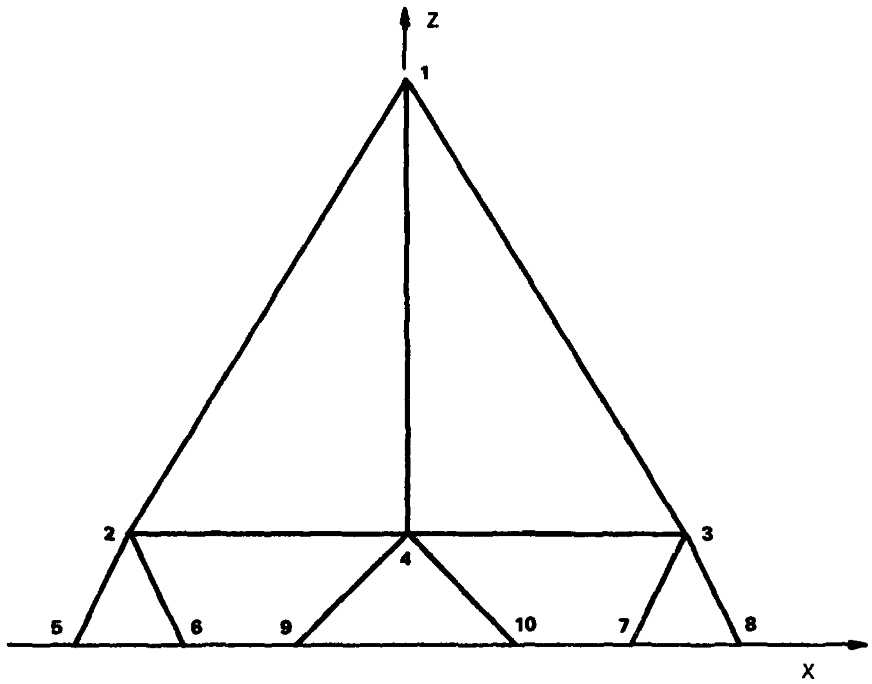
This has been demonstrated by the effective application of decentralized control systems by Miller (Ref 1) and Aldridge (Ref 3) to the CSDLI model.

The finite element model of the structure is shown in Fig. 1. The structure consists of twelve members connected by pinned joints at ten nodes. This allows axial forces in the members, but no bending moments. The members are considered massless. Equal masses of one unit each are lumped at the four vertices of the tetrahedron (nodes one through four). Each of the four masses has three translational degrees of freedom giving the system model a total of twelve structural modes. Nodes five through ten anchor the three right angled bipods which support the tetrahedral truss above the ground. These six nodes are fixed so that the ground plane forms a frame of reference from which deflection criteria may be established and measured. The coordinates of the ten nodes are listed in Table I.

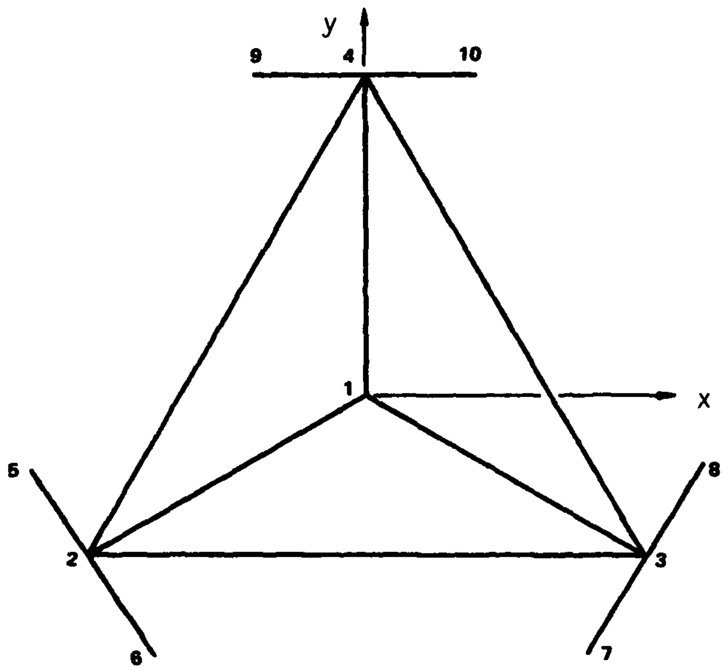
TABLE I

CSDLI NODE COORDINATES

NODE	X	Y	Z
1	0.0	0.0	10.165
2	-5.0	-2.887	2.0
3	5.0	-2.887	2.0
4	0.0	5.774	2.0
5	-6.0	-1.155	0.0
6	-4.0	-4.619	0.0
7	4.0	-4.619	0.0
8	6.0	-1.155	0.0
9	-2.0	5.774	0.0
10	2.0	5.774	0.0



SIDE VIEW



TOP VIEW

FIGURE 1: CSDLI MODEL

The origin of the coordinate frame lies in the ground plane beneath node one. The Y-axis lies in the ground plane along the projection on the ground of the member joining nodes one and four and the X-axis forms a right-handed set.

Six pair of collocated actuators and sensors are placed on the six ground connected members to implement the control system. Appendix A presents the actuator direction matrix, D, which, in the case of collocated actuators and sensors, is also the transpose of the sensor direction matrix, C. Also included in Appendix A, are the frequencies and eigenvectors for the two variations of the CSDLI model that are used in this study. This data was obtained by NASTRAN eigenstructure analyses.

This study uses line of sight, based on the deflection of node one from the Z-axis, as its measure of controller performance. Any motion of node one in the Z direction is considered unimportant to performance. The initial conditions listed in Table II are applied to the models and time histories of the system responses are computed.

The program developed by Aldridge (Ref 3) was modified to include output of the integrated total expended control effort in the time history. The integrated control effort as it relates to the reduction in line of sight deflection can then be used to evaluate control system "efficiency". The line of sight deflection and system efficiency performance parameters are discussed more fully in later chapters.

TABLE II

CSDLI INITIAL CONDITIONS IN PHYSICAL COORDINATES

MODE	DISPLACEMENT(q)	VELOCITY($\dot{q}$)
1	-.00255	-.00180
2	-.00082	-.00039
3	.00394	-.00175
4	-.0039	-.00589
5	-.00458	-.02141
6	.00352	.00740
7	.00031	-.00327
8	-.00379	-.00568
9	-.00028	-.00363
10	-.00058	-.01546
11	-.00499	-.01586
12	.00015	-.00398

III. THE COMPUTER MODEL

In order to test new theories, to validate structural or controller design techniques, or to test actual designs, a computer simulation is needed that can serve as a testbed. The ACOSS2 program developed by E.S. Aldridge (Ref 3) forms an ideal base on which to build such a testbed. This program receives input of structural and control configuration data. From this, it forms a multiple controller system capable of handling the large number of modes required to control a large, flexible structure. The program then decentralizes or decouples the multiple control system into independent systems. The control system designed by this program is output in the form of controller and estimator (or observer) gains. Eigenvalue analyses of the total system both before and after the decoupling are also computed. With the input of modal initial conditions, a time history of the structural response may be computed.

In the attempt to develop a testbed program from this base, several qualities appear to be desirable: 1) flexibility in the inputs, 2) minimum outside computation, and 3) inclusion of the machinery necessary to generate any information that might be useful. Improvement in these three areas is the motivation behind the modifications that are described in this chapter.

This chapter consists of two sections. The first contains a summary of the development of multiple controller systems as presented in Ref 3. The second draws on the development of the first in order to describe the modifications that have been made in the ACOSS2 program.

The Multiple Controller System

As presented by Calico and Miller (Refs 1 and 2), the system model for any structure may be developed from the vibrational equations of motion in the form

$$M\ddot{\bar{q}} + E\dot{\bar{q}} + K\bar{q} = D\bar{u} \tag{1}$$

where

M = nxn symmetric mass matrix

E = nxn symmetric damping matrix

K = nxn symmetric stiffness matrix

$\bar{q}$ = nx1 physical coordinate vector

$\bar{u}$ = mx1 control input vector

By introducing the nxn modal matrix for Eq 1, such that

$$\bar{q} = \Phi * \bar{n}$$

where $\bar{n}$ is the n-vector of modal coordinates, and premultiplying by Φ^T, Eq 1 becomes

$$\Phi^T M \Phi \ddot{\bar{n}} + \Phi^T E \Phi \dot{\bar{n}} + \Phi^T K \Phi \bar{n} = \Phi^T D\bar{u} \tag{2}$$

Due to the properties of the modal matrix, Eq 2 simplifies to

$$\begin{bmatrix} \diagdown & & \\ & I & \\ & & \diagdown \end{bmatrix} \ddot{\bar{n}} + \begin{bmatrix} \diagdown & & \\ & 2\zeta\omega & \\ & & \diagdown \end{bmatrix} \dot{\bar{n}} + \begin{bmatrix} \diagdown & & \\ & \omega^2 & \\ & & \diagdown \end{bmatrix} \dot{\bar{n}} = \Phi^T D\bar{u} \tag{3}$$

The ω_i and ζ_i being the natural frequencies and damping coefficients respectively of the individual modes. Equation 3 can now be written in state space form as

$$\dot{\bar{x}} = A\bar{x} + B\bar{u} \tag{4}$$

where

$$A = \left[\begin{array}{c|c} 0 & I \\ \hline -\omega^2 & -2\zeta\omega \end{array}\right]$$

$$B = \left[\begin{array}{c} 0 \\ \hline \Phi^T D \end{array}\right] \tag{5}$$

and

$$\bar{x} = \begin{bmatrix} \bar{n} \\ \dot{\bar{n}} \end{bmatrix}$$

Because the complete state is not normally available, Eq 4 is supplemented by the sensor output equation

$$\bar{y} = C_p\bar{q} + C_v\dot{\bar{q}} \tag{6}$$

where the p and v subscripts designate position and velocity. In terms of the state vector $\bar{X}$ this is expressed as

$$\bar{y} = C\bar{x} \tag{7}$$

where

$$C = [C_p \ \vdots \ C_v\ ] \tag{8}$$

when only position sensors are used, Eq 8 becomes

$$C = [C_p \ \vdots \ 0] \tag{9}$$

Further if collocated actuators and sensors are used

$$\bar{y} = [D^T \Phi \mid 0] = [[\Phi^T D]^T \mid 0] \tag{10}$$

The program reads the C matrix in transposed form to take advantage of this simplicity, but does not require that C equal D transported. Equations 4 and 9 form the state space model that is used to design the control system.

This study will use the three controller program configuration with no modes left uncontrolled (no residual modes). The following development of a multiple controller system, therefore, assumes this configuration. For a four controller system or three controllers with residuals, the reader is referred to Ref 3.

For three controllers, each controlling a subset n_i of the controlled modes, the state vector $\bar{x}$ is simply represented as

$$\bar{x} = \left\{ \bar{x}_1^T, \bar{x}_2^T, \bar{x}_3^T \right\}^T \tag{11}$$

The $\bar{x}_i$ terms represent $2n_i$-vectors that are the state vectors of the three controllers. In the form of Eqs 4 and 9, the state equation models of the individual controllers are

$$\dot{\bar{x}}_i = A_i \bar{x}_i + B_i \bar{u} \tag{12}$$

and

$$\bar{y} = \sum_{i=1}^{3} C_i \bar{x}_i \tag{13}$$

where the A_i, B_i, and x_i have the form of Eq 5 and the C_i have the form of Eq 9. Now, the desired state feedback control has the form

$$\bar{u} = \sum_{i=1}^{3} G_i \bar{x}_i \tag{14}$$

where G_i are the control gain matrices.

As mentioned earlier, the entire state vector is not normally available, so an estimator is needed to estimate $\bar{x}$ from the observations $\bar{y}$. This estimator takes the form

$$\dot{\hat{x}}_i = A_i \hat{x}_i + B_i \bar{u} + K_i(\bar{y} - \hat{y}_i) \tag{15}$$

where

$$\hat{y}_i = C_i \hat{x}_i \tag{16}$$

and $\wedge$ represents an estimated vector. The K_i are the estimator gains and are chosen so that the state estimate error

$$\bar{E}_i = \hat{x}_i - \bar{x}_i \tag{17}$$

is asymptoticly stable. Now, the control vector is redefined in terms of the estimated state by

$$\bar{u} = \sum_{i=1}^{3} G_i \hat{x}_i \tag{18}$$

where

$$\hat{x}_i = \bar{x}_i + \bar{E}_i \tag{19}$$

The controller and estimator gains are computed using linear optimal regulator theory. Regulator theory is developed very completely in

Kwakernaak (Ref 4) and is applied specifically to our case in (Ref 3). This development needs only the fact that gains found by regulator theory minimize the quadratic cost function (or performance index) J defined by

$$J = 1/2 \int_0^{\infty} (\bar{x}_i^T Q_i \bar{x}_i + \bar{u}^T R_i \bar{u}) dt \qquad (20)$$

where

Q is an nxn positive semidefinite response weighting matrix

R is an mxm positive definite control weighting matrix subject to Eq 12. In the ACOSS2 program, the R matrices are all the identity and the response weighting is restricted to being diagonal with the diagonal elements input by mode.

Once the control and estimator gains are computed, the program forms an augmented state equation that may be integrated to form the time history of the state vector. This is done by forming an augmented state vector $\bar{z}$ given by

$$\bar{z} = \left\{ \bar{x}_1^T, \bar{E}_1^T, \bar{x}_2^T, \bar{E}_2^T, \bar{x}_3^T, \bar{E}_3^T \right\}^T \qquad (21)$$

where

$$\bar{E}_i = \begin{Bmatrix} \bar{e}_i \\ \dot{\bar{e}}_i \end{Bmatrix} \qquad (22)$$

Expressing Eq 12 in terms of $\bar{z}$ and forming an $\dot{\bar{e}}$; Equatio..

Eq 12 in terms of state $\bar{z}$ elements are

$$\dot{\bar{x}}_i = (A_i + B_i G_i)\bar{x}_i + B_i G_i \bar{e}_i + \sum_{\substack{j=1 \\ j \neq i}}^{3} B_i G_j (\bar{x}_j + \bar{e}_j) \quad i = 1,2,3 \qquad (23)$$

Differentiating Eq 17 gives

$$\dot{\bar{e}}_i = \dot{\hat{x}}_i - \dot{\bar{x}}_i \tag{24}$$

Then combining Eqs 15, 16, 19, and 23 yields

$$\dot{\bar{e}}_i = (A_i - K_i C_i)\bar{e}_i + \sum_{\substack{j=1 \\ j \neq i}}^{3} K_i C_i \bar{x}_j \qquad i=1,2,3 \tag{25}$$

In matrix form, the closed-loop state equation in terms of $\bar{z}$ is

$$\dot{\bar{z}} = \begin{bmatrix} A_1+B_1G_1 & B_1G_1 & B_1G_2 & B_1G_2 & B_1G_3 & B_1G_3 \\ 0 & A_1-K_1C_1 & K_1C_2 & 0 & K_1C_3 & 0 \\ B_2G_1 & B_2G_1 & A_2+B_2G_2 & B_2G_2 & B_2G_3 & B_2G_3 \\ K_2C_1 & 0 & 0 & A_2-K_2C_2 & K_2C_3 & 0 \\ B_3G_1 & B_3G_1 & B_3G_2 & B_3G_2 & A_3+B_3G_3 & B_3G_3 \\ K_3C_1 & 0 & K_3C_2 & 0 & 0 & A_3-k_3C_3 \end{bmatrix} \bar{z} \tag{26}$$

The solution to this differential equation is

$$\bar{z} = \mathrm{EXP}[At] * \bar{z}(o) \tag{27}$$

where A is the matrix of Eq 26. This is the solution that is propagated to form the response time history. Note that knowledge of the state $\bar{z}$ is not a very useful output. The state $\bar{z}$ is a vector of modal coordinates reordered into three controllers, each controller state being augmented

with an error term. The method used by the program to extract useful information is discussed in the following section of this chapter.

Decentralization or decoupling of the controllers is accomplished by lower block triangularization of the matrix in Eq 26. This is done by insuring that the proper combination of control and observation spillover is eliminated by the decoupling transformations developed in Ref 3. As discussed in the Investigation and Results section, this transformation is not always necessary and it may reduce the efficiency of the control system.

Program Modifications

As mentioned earlier in this chapter, three goals of this modification were flexibility in the input, minimum outside computation, and the ability to generate any needed output. The changes made in the program in the course of this study reflect improvements in each of these areas. Further study, however, may well reveal other advantageous revisions. Certainly, the unique needs of particular tests will require small changes.

The following presents the modifications made thus far. They are discussed in the order that the program encounters them. Because only the modifications are discussed, ties to the previous section will be few, but equation numbers are given where applicable. The variable and matrix names used by the program are either used in the discussion or listed in parentheses. The FORTRAN code of these modifications, as well as a program flowchart and a sample data file are included as Appendix B. Where possible, a few lines before and/or after the change are listed to show location in the program.

The first change alters the way in which the structural and control hardware information are input. Because sensor and actuator location are logical test variables, direct inputs of $\Phi^T D$ (Eq 2) (PHIA) and $C\Phi$ (Eq 9) (PHIS) were changed to allow separate inputs of Φ (PHI), D (DMAT), and C (CMAT). Matrices PHIA and PHIS are then computed internal to the program. Now the only outside computation required is a NASTRAN analysis of the structure and the assemblage of the C and D orientation matrices. Here a new subroutine, TANGL, computes the angles between the rows of PHIA. As mentioned by Miller (Ref 1), the choice of modal groupings within individual controllers is an important consideration. According to Miller, the angles between the control forces applied to the modes within a single controller should be kept as small as possible. This point is the subject of a quantitative investigation later in this study.

Another change in the input is the addition of an option to input the initial conditions in either modal coordinates (INIT) or physical coordinates (GNIT). This option is presently assigned by initialization of the variable INCOND within the source program. For the purpose of this study, equal initial conditions in physical variables were required for the fair comparison of two structural designs. If modal input is chosen, the physical coordinates are computed and output for comparison. The program uses modal coordinates to form the controllers and the time history without regard to the choice of input.

The line of sight matrix (CLOS) that extracts the performance parameters for the time history is input as in ACOSS2. However, it should be noted here that its use has been altered significantly. This will be discussed in detail later. Input of the diagonal values of the

weighting matrix (Eq 20) (BB) changed, however, these values now set only the relative weighting between the modes. The magnitudes of these values are then scaled by the value of SCALEB which is read from data during the program initializations.

The only change in the section that forms the individual controller matrices (Eqs 12 & 13) (A1-A3, B1-B3, C1-C3) is the addition of the formation of PHI1-PHI3. These matrices consist of columns containing the eigenvectors of the individual controllers. They are generated by subroutine FORMPHI and are used later in the program to form the reordered modal matrix (PHINEW).

The remainder of the changes deal with the machinery used to extract useful time histories from the augmented state vector, Z (Eq 27). These changes are contained in the area of the main program just before subroutines YHAT and TIME and in the subroutines themselves. The program stores the matrix of Eq 26 in array MAJM so that the solution to Eq 27 is

$$\bar{z} = \exp\,[\mathrm{MAJM}*t] * \bar{z}(o) \qquad (28)$$

where

$$\bar{z} = \left\{\bar{n}_1,\dot{\bar{n}}_1,\bar{e}_1,\dot{\bar{e}}_1\bar{n}_2\dot{\bar{n}}_2,\bar{e}_2,\dot{\bar{e}}_2,\bar{n}_3\dot{\bar{n}}_3,\bar{e}_3,\dot{\bar{e}}_3\right\}^T$$

and $\bar{z}(0)$ has been formed from the modal initial condition matrix (INIT) by FORMXØ. The state, $\bar{z}(0)$, is then propagated by subroutine time to arrive at $\bar{z}(t)$. However, as previously mentioned, $\bar{z}(t)$ is a combination of modal coordinates and their rates as well as observation error and error rate terms. The program uses a series of matrices to extract the physical coordinates, $\bar{q}(t)$, from the full state, $\bar{z}(t)$. To obtain a reordered set of modal coordinates, YHAT forms the matrix PETA such that

$$\text{PETA} * \bar{z} = \begin{bmatrix} \bar{n}_1 \\ \bar{n}_2 \\ \bar{n}_3 \end{bmatrix} \tag{29}$$

where $\bar{n}_i$ is the modal coordinate vector for the i^{th} controller. The main program has formed the matrix PHINEW of reordered mode shapes so that

$$\bar{q} = \Phi\bar{n} = \text{PHINEW} * \begin{bmatrix} \bar{n}_1 \\ \bar{n}_2 \\ \bar{n}_3 \end{bmatrix} \tag{30}$$

where $\bar{q}$ is the physical coordinate vector (Eq 1) in its original order. This is true because the columns of PHI were reordered to form PHINEW in the same manner that the rows of $\bar{n}$ where reordered to form $\left\{\bar{n}_1^T, \bar{n}_2^T, \bar{n}_3^T\right\}^T$.

The structural time response of interest to the designer may be individual physical coordinates, a linear coordination of physical coordinates, or a nonlinear function of coordinates. The matrix CLOS is used by the program to form desired response vector, XLOS, from the physical state so that

$$\text{XLOS} = \text{CLOS} * \bar{q} \tag{31}$$

If a nonlinear function is the desired performance parameter, CLOS may be used to extract the states that are needed, and the function may then be computed. The present study uses this method to form the deflection parameter which is a nonlinear function of the x and y coordinates of node one. Combining Eqs 29, 30, and 31 yields

$$\text{XCLOS} = \text{CLOS} * \text{PHINEW} * \text{PETA} * \bar{z} \tag{32}$$

This use of CLOS differs from the ACOSS2 program which uses a matrix V in place of PHINEW. The matrix V transforms $\left\{\bar{n}_1^T, \bar{n}_2^T, \bar{n}_3^T\right\}^T$ into the vector $\bar{y}$ of sensor output. It was found that this method makes the formation of CLOS unnecessarily complicated if, indeed, a physical response parameter is the goal. The machinery for forming V was not removed, however, so that the sensor output time history can be formed with reasonable effort.

Subroutine YHAT multiples CLOS * PHINEW and calls the product CV, forms PETA, and then performs CV*PETA calling the new matrix XHAT. Equation 32 may now be written

$$\text{XLOS} = \text{XHAT}*\bar{z} \qquad (33\_$$

which is the form used by subroutine TIME to form the time history.

A procedure similar to the formation of XLOS is used to form the control vector, $\bar{u}$ (UBAR). Since

$$\bar{u} = \sum_{i=1}^{3} G_i\hat{x}_i \qquad (34)$$

The estimated state, x_i must be formed. From Eq 19

$$\hat{x}_i = \left\{\bar{x}_i + \bar{E}_i\right\} = \begin{Bmatrix} \bar{n}_i + \bar{e}_i \\ \dot{\bar{n}}_i + \dot{\bar{e}}_i \end{Bmatrix} \qquad (35)$$

To extract the x_i, subroutine YHAT forms PXHT so that

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \text{PXHT}*\bar{z} \qquad (36)$$

To form and sum the products $G_i x_i$, the main program forms a partitioned matrix of controller gains

$$GPART = [G_1 \mid G_2 \mid G_3] \tag{37}$$

Now $\bar{u}$ is formed easily by

$$\bar{u} = [GPART] \begin{bmatrix} \bar{x}_1 \\ \bar{x}_2 \\ \bar{x}_3 \end{bmatrix} = \sum_{i=1}^{3} G_i x_i \tag{38}$$

Combining Eqs 36 and 38 yields

$$\bar{u} = UHAT * \bar{z} \tag{39}$$

where

$$UHAT = GPART*PXHT \tag{40}$$

With UHAT input into subroutine TIME, $\bar{u}(t)$ is readily formed from the augmented state, $\bar{z}(t)$. The present study, however, uses the integrated or total expended control force as the parameter of interest. To perform the integration of the control force, a trapezoidal integration scheme is included in subroutine TIME. Direct output of $\bar{u}(t)$ is possible without removal of the integration section by simply altering the WRITE statement.

With this machinery in place, it is hoped that the minor modifications needed to suit the needs of a particular test may be accomplished with relative ease. At this time, however, the warning contained in the recommendation section should be considered the probable causes of any unexplainable major problems.

IV. INVESTIGATION

Control of large space structures is a complex task that must be carefully dissected to be fully understood. Complete knowledge of the problem and the possible paths to the "best solution" requires a thorough knowledge of the individual factors involved and of the sensitivity of each factor to changes in the others. The studies done by Miller and Aldridge show that multiple controller systems are both needed and viable as solutions to the space structure control problem. This investigation has two thrusts; first, to quantitatively test two qualitative insights mentioned in the previous studies. These deal with the grouping of modes into controllers by the angles between the vectors of modal amplitudes (between the rows of $\Phi^T D$) and the general tendency of the decoupling transformation to reduce system stability. These areas are studied individually and in relation to one another. The second thrust is to demonstrate a method of comparing the efficiency of one structure/controller design with that of another design.

Test Cases

Four structure/controller configurations are tested. Three are comprised of control configuration changes on the nominal structure and the fourth uses the deflection design to demonstrate the considerations necessary to fairly compare two structural designs.

Several factors of the control configuration remain unchanged from case to case. The program is used only in the three controller configuration with four of the twelve structural modes in each controller. A structural damping ratio of 1/2% (.005) is applied to each mode. The six pair of collocated actuators and sensors are located on the six members

which support the tetrahedral truss. The modal initial conditions used by Miller are applied to the cases involving the nominal structure. The program output for the nominal structure includes initial conditions in physical coordinates. These values are used for the case using the frequency designed structure so that the physical initial conditions are constant over the four cases.

The response weighting matrix, Q, is the varied parameter within the tests, but the values used are the same for the four tests. Q is input as the identity and scaled by the value of SCALEB in the program. Since specific response requirements were not the goal, the range of SCALEB used in the tests was chosen solely for clarity of presentation. By a rough search of a few orders of magnitude, a suitable range was found to be 0.1 through 1.0. To obtain clear separation between runs, the values used were 1E-10, 0.04, 0.1, 0.2, 0.5, 0.8, and 1.0. The first two values were added to complete information needed to form the plots in the next chapter.

The three nominal design cases are separated by the manner in which the modes are assigned to the controllers and by whether or not the decoupling transformation was included in the controller design. A modal grouping that minimizes the angles between the modes within a controller is referred to as favorable. An unfavorable grouping assigns orthogonal modes to the same controller and modes with a small relative angle to separate controllers. Certainly, there are varying degrees of unfavorable groupings. This study, however, uses only the worst available grouping to represent unfavorable. The transformation that block triangularizes the system matrix has been shown to lessen the damping originally achieved by the controllers. While the transformation guarantees overall system stability, it is quite possible

that some control configurations are stable before triangularized. The configurations that were tested are now presented case by case.

Case I. The nominal structure modes are grouped favorably, and the decoupling transformation is used. Table III presents the relative angles for the nominal structure modes as computed by the program. The most favorable grouping is given by

Controller 1: 2,3,8,9

Controller 2: 5,6,11,12

Controller 3: 1,4,7,10

Case II. The nominal structure modes retain the favorable grouping of Case I, but the decoupling transformation is omitted.

Case III. The nominal structure modes are grouped unfavorably. From Table III, one of the most unfavorable groupings is

Controller 1: 2,3,4,6

Controller 2: 1,5,7,9

Controller 3: 8,10,11,12

Of the six modal angles in each controller, Controller 1 has five that are essentially 90°, Controller 2 has four that are orthogonal, and Controller 3 has five angles greater than 87°. The decoupling transformation is included in the controller design for this case.

Case IV. The deflection designed structure modes are grouped favorably, and the decoupling transformation is performed. This case is intended to represent the best possible control configuration for the deflection design. The reasons for its choice are discussed in the next section. Table IV presents the angles between the modes of this structure.

TABLE III

RELATIVE ANGLES* BETWEEN NOMINAL DESIGN MODES

MODE	1	2	3	4	5	6
1	.00	89.99	-90.00	66.58	90.00	89.99
2	89.99	0.00	64.38	89.99	-83.28	89.99
3	-90.00	64.38	0.00	-90.00	85.33	90.00
4	66.58	89.99	-90.00	0.00	-90.00	90.00
5	90.00	-83.28	85.33	-90.00	0.00	90.00
6	89.99	89.99	90.00	90.00	90.00	0.00
7	33.16	90.00	90.00	-80.25	90.00	-90.00
8	90.00	-50.03	68.61	89.99	-84.41	-90.00
9	89.99	32.74	34.86	89.98	-77.88	90.00
10	-51.61	89.99	89.97	-14.98	-89.99	-90.00
11	-90.00	-85.04	-61.81	-90.00	-23.55	-90.00
12	89.99	71.78	-89.56	89.99	-11.54	-90.00

MODE	7	8	9	10	11	12
1	33.16	90.00	89.99	-51.61	-90.00	89.99
2	90.00	-50.03	32.74	89.99	-85.04	71.78
3	90.00	68.61	34.86	89.97	-61.81	-89.56
4	-80.25	89.99	89.98	-14.98	-90.00	89.99
5	90.00	-84.41	-77.88	-89.99	-23.55	-11.54
6	-90.00	-90.00	90.00	-90.00	-90.00	-90.00
7	0.00	90.00	90.00	-84.77	90.00	90.00
8	90.00	0.00	-82.76	-90.00	-87.56	-87.15
9	90.00	-82.76	0.00	90.00	-81.24	68.92
10	-84.77	-90.00	90.00	.00	-90.00	-90.00
11	90.00	-87.56	-81.24	-90.00	0.00	30.03
12	90.00	-87.15	68.92	-90.00	30.03	0.00

*Angles in degrees

TABLE IV

RELATIVE ANGLES BETWEEN DEFLECTION DESIGN MODES

MODE	1	2	3	4	5	6
1	0.00	-36.26	-30.05	-41.05	37.46	-26.60
2	-36.26	0.00	48.91	46.63	-39.98	39.52
3	-30.05	48.91	0.00	27.23	-35.15	42.97
4	-41.09	46.63	27.23	.00	-33.62	53.46
5	37.46	-39.98	-35.15	-33.62	0.00	-54.94
6	-26.60	39.52	42.97	53.46	-54.94	0.00
7	77.70	-73.27	77.03	83.63	78.40	-77.35
8	85.84	77.10	72.72	57.87	-67.80	-84.36
9	70.04	-75.67	-78.68	-86.91	-85.15	-76.01
10	84.28	87.57	-80.61	75.70	84.61	-79.37
11	82.51	67.68	-77.52	-80.55	79.57	79.99
12	88.38	76.65	-87.45	-88.67	-71.07	-70.55

MODE	7	8	9	10	11	12
1	77.70	85.84	70.04	84.28	82.51	88.38
2	-73.27	77.10	-75.67	87.57	67.68	76.65
3	77.03	72.72	-73.68	-80.61	-77.52	-87.45
4	83.63	57.87	-86.91	75.70	-80.55	-88.67
5	78.40	-67.80	-85.15	84.61	79.57	-71.07
6	-77.35	-84.36	-76.01	-79.37	79.99	-70.55
7	0.00	67.05	-77.41	-82.43	-87.85	-84.36
8	67.05	0.00	62.53	78.34	77.35	82.48
9	-77.41	62.53	0.00	-81.96	-87.27	-81.17
10	-82.43	78.34	-81.96	0.00	-89.11	-85.72
11	-87.85	77.35	-87.27	-89.11	0.00	88.75
12	-84.36	82.48	-81.17	-85.72	88.75	0.00

*Angles in degrees

The most favorable grouping, though not so obvious as for the nominal design, appears to be

Controller 1: 3,4,5,11

Controller 2: 1,2,6,12

Controller 3: 7,8,9,10

The modified program is run seven times on each test case varying only the scale of the response weighting matrix. The output of interest is the time history generated by application of the given initial conditions for each case and weighting matrix. The parameters included in each time history are the x and y coordinates of Node 1, the radius of deflection for node 1, the integrated effort of each actuator, and the total integrated effort for all actuators. The following section presents and discusses the results obtained from these computer runs.

VI. RESULTS

Six time response simulations were performed on each of the four test cases described in the previous section. Different controller and estimator gains were designed for each simulation within a test case by varying the response weighting matrix, Q. In this chapter, the factor used to scale Q will be referred to as α_Q so that α_Q is the varied parameter within a test case. In addition, uncontrolled responses to the initial conditions were approximated for both structural designs by setting α_Q equal to 1E-10. This value of α_Q resulted in zero gains for all controllers and zero expended control effort. The data obtained from these simulations is presented in the form of three plots for each test case. While the plots contain axes labelled in terms of force and distance, no units are given. This is because the units are of no consequence to this study as long as consistent mass, distance, force, and stiffness units are used so that the natural frequencies are in hertz.

The first plot contains the response envelopes for the values of that were used. As mentioned earlier, the x- and y- line of sight parameters used in previous studies on this model have been used to form a single response parameter, the deflection node one from the z-axis. The use of a single response parameter simplifies comparison of responses. Also, the radius of deflection time history can be described by a single response envelope because it is always a positive quantity. Figure 2 demonstrates the formation of a typical response envelope. It should be noted that the determination of the response envelope from the complete time history is somewhat subjective. The time step used (0.01 sec) was sufficiently small to show the oscillations completely. Still, the peaks

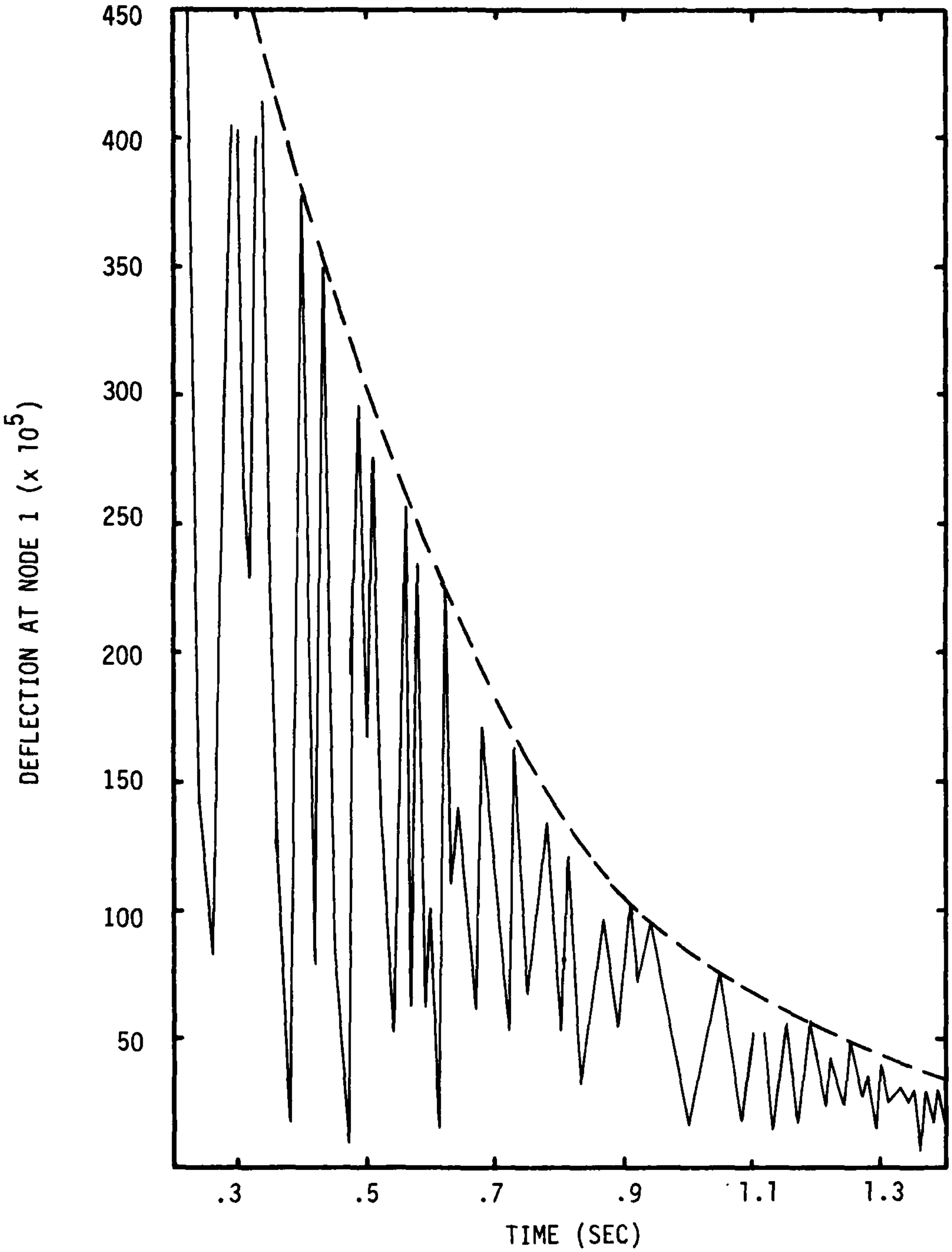


FIGURE 2: TYPICAL RESPONSE ENVELOPE

of individual oscillations were not always well defined. The height of peaks located in the center of a time interval was impossible to determine accurately. This problem is illustrated clearly on Figure 2 at about 0.3 seconds. When the height of an oscillation was very uncertain, the peak was not plotted. Each point plotted is subject to some levels of error due to the discrete nature of the time history. Because these errors always cause a lowering of the peaks from the actual, the response envelope was not allowed to fall below any point of the time history. Scatter in the data is due to these errors.

This problem was magnified on the frequency design to the extent that no reasonable approximation to the response envelopes could be made. This was corrected by reducing the time step to .005 sec for Case IV. Figures 3, 6, 9, and 12 present the response envelope plots for the four test cases.

Integrated control effort time histories for each simulation were also plotted. As expected, these curves asymptotically approach maximum values as the decreasing magnitude of the response requires reduced expenditure of control effort. These curves are smooth with no real scatter in the data, so no data are shown. The control response curves for the test cases are presented in Figures 4, 7, 10, and 13.

By combining data from these two curves, curves showing the control configuration performances were formed. This was done by taking sections of the response envelope and control response plots at a given time as illustrated on Figures 3 and 4. These plots contain families of curves with α_a as the parameter. Using the sections, the deflection time at time t may be plotted versus the integrated control force at time t for each value of α_a used. In the absence of prespecified performance

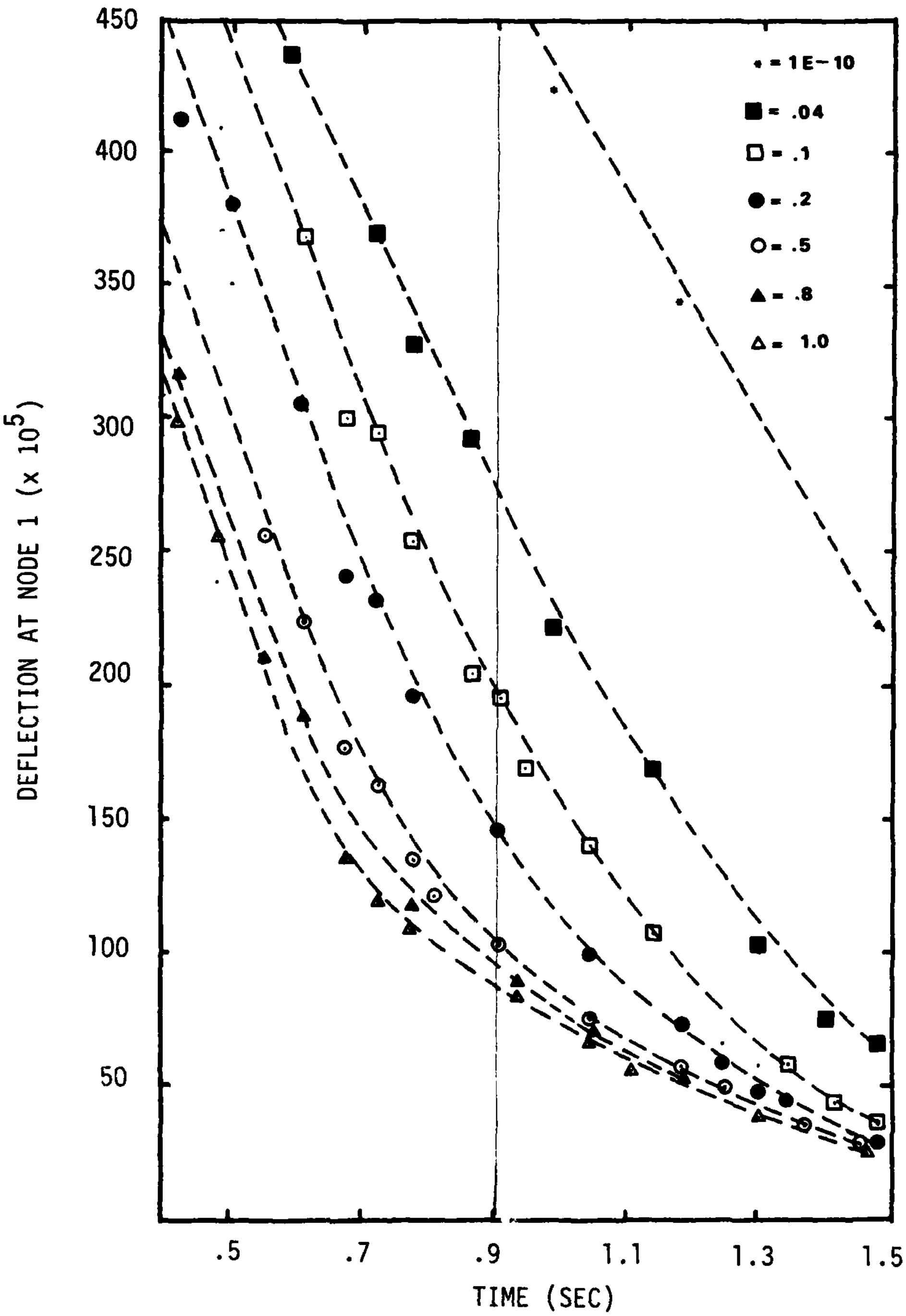


FIGURE 3: CASE I RESPONSE ENVELOPE WITH Q AS PARAMETER

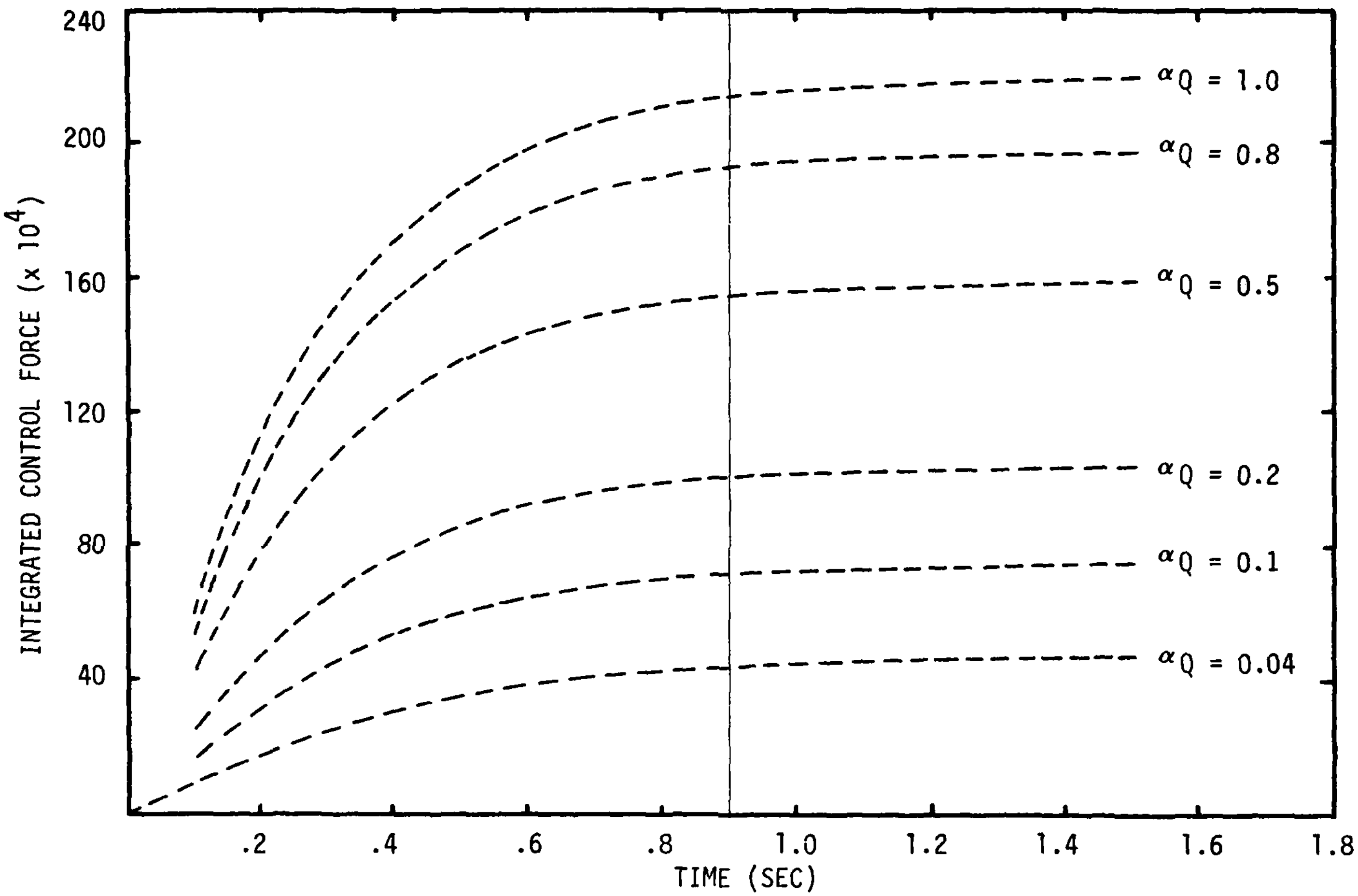


FIGURE 4: CASE I CONTROL EFFORT WITH Q AS PARAMETER

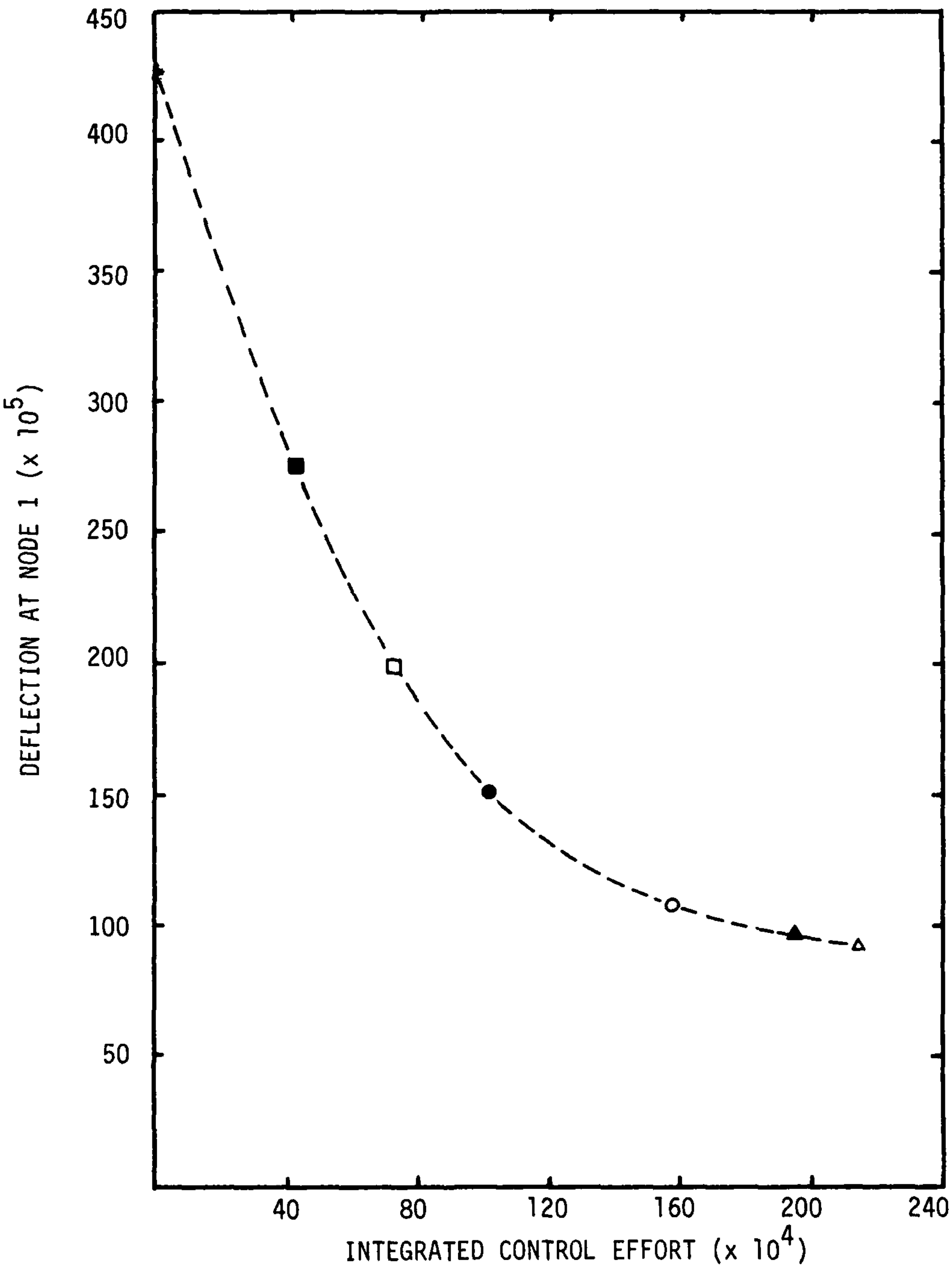


FIGURE 5: CASE I SYSTEM PERFORMANCE CURVE

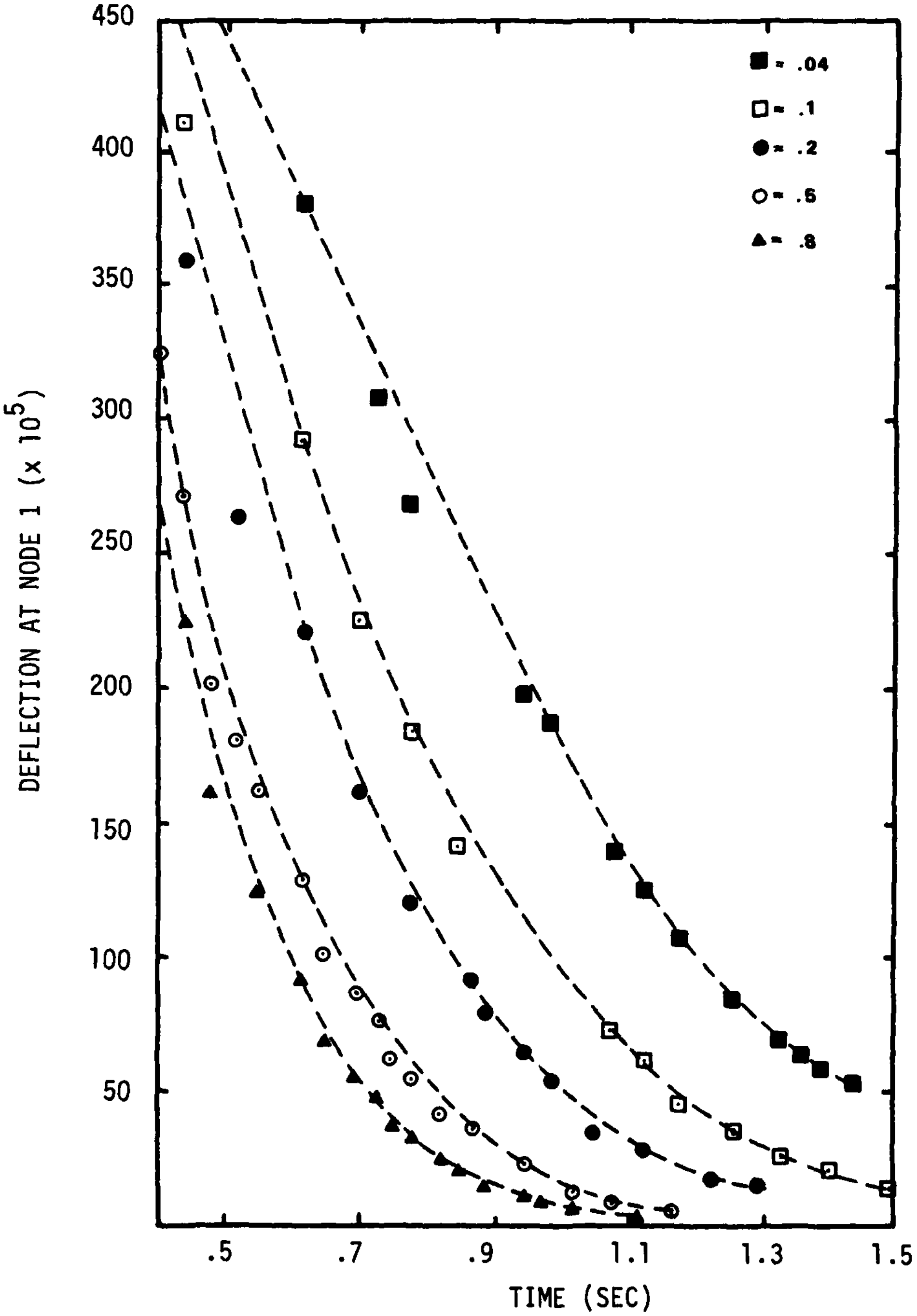


FIGURE 6: CASE II RESPONSE ENVELOPE WITH Q AS PARAMETER

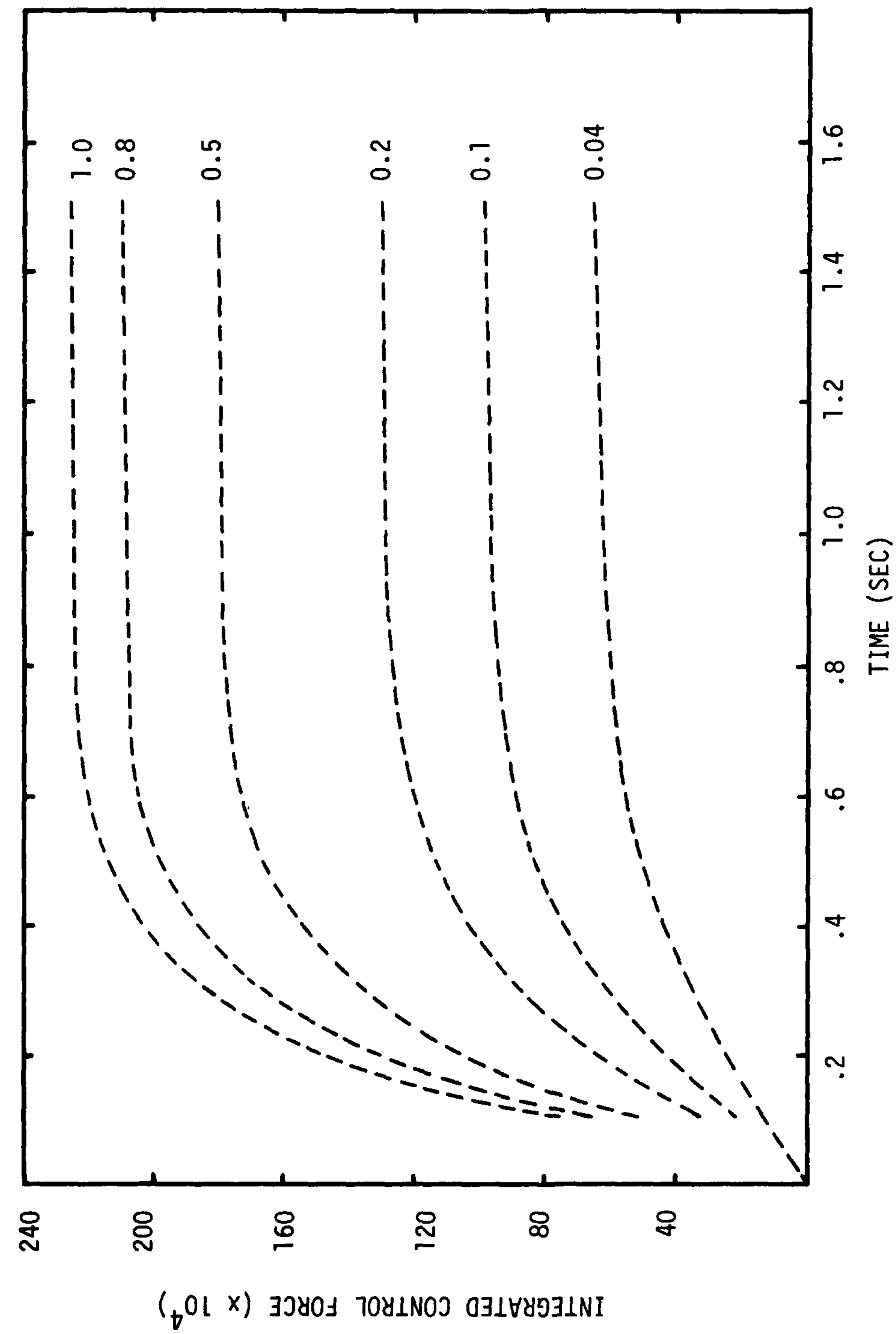


FIGURE 7: CASE II CONTROL EFFORT WITH Q AS PARAMETER

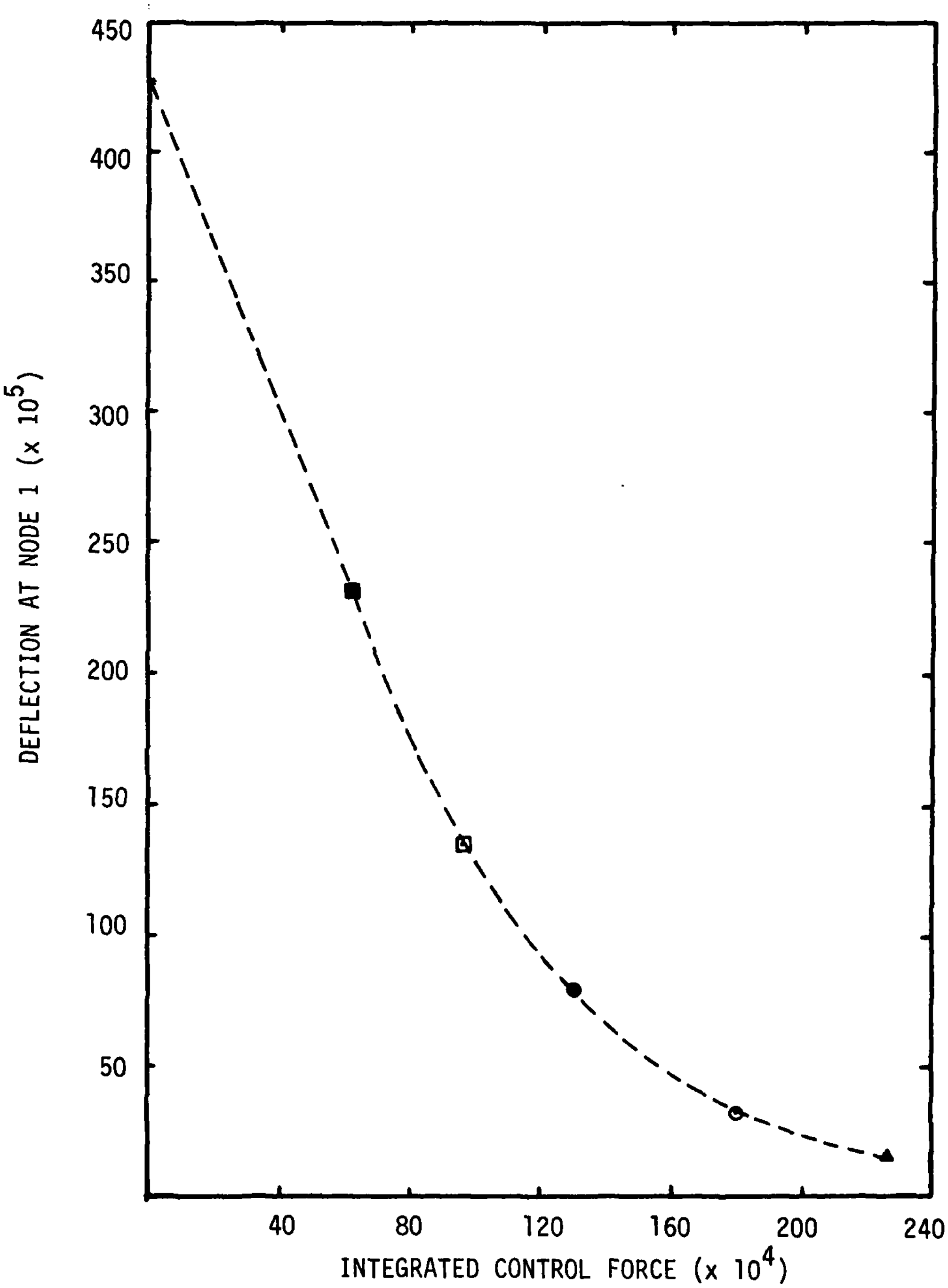


FIGURE 8: CASE II SYSTEM PERFORMANCE CURVE

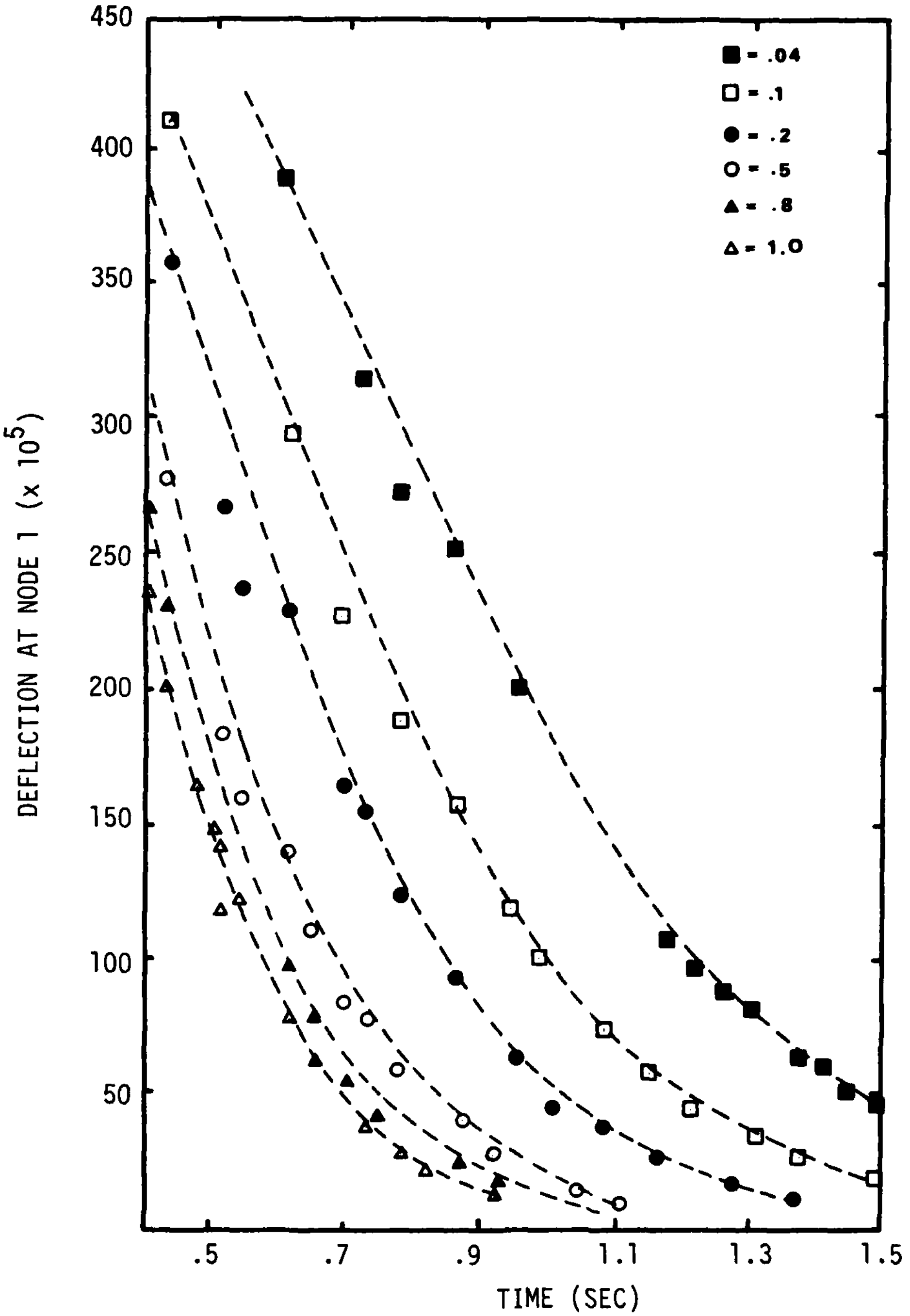


FIGURE 9: CASE III RESPONSE ENVELOPE WITH Q AS PARAMETER

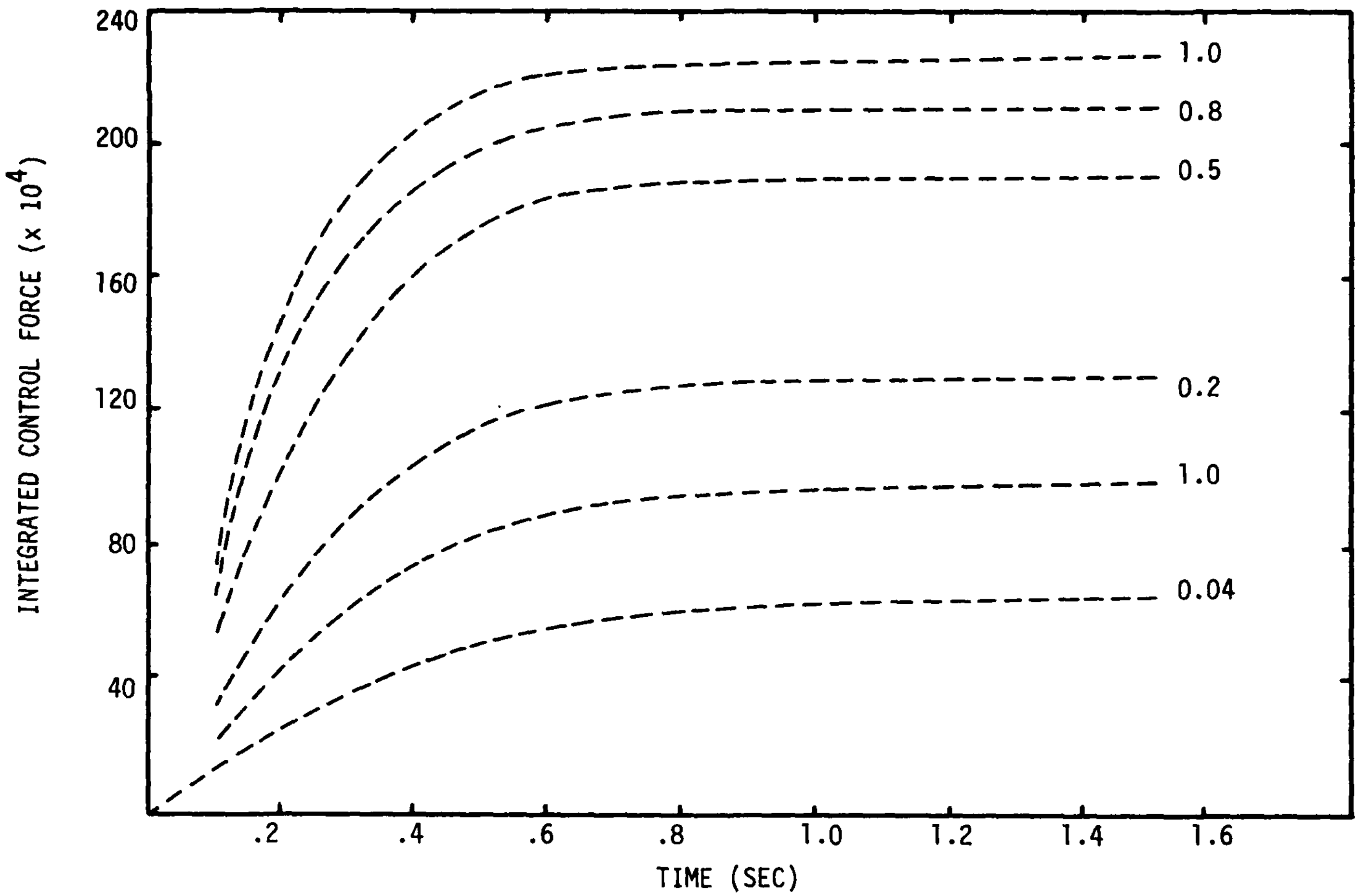


FIGURE 10: CASE III CONTROL EFFORT WITH Q AS PARAMETER

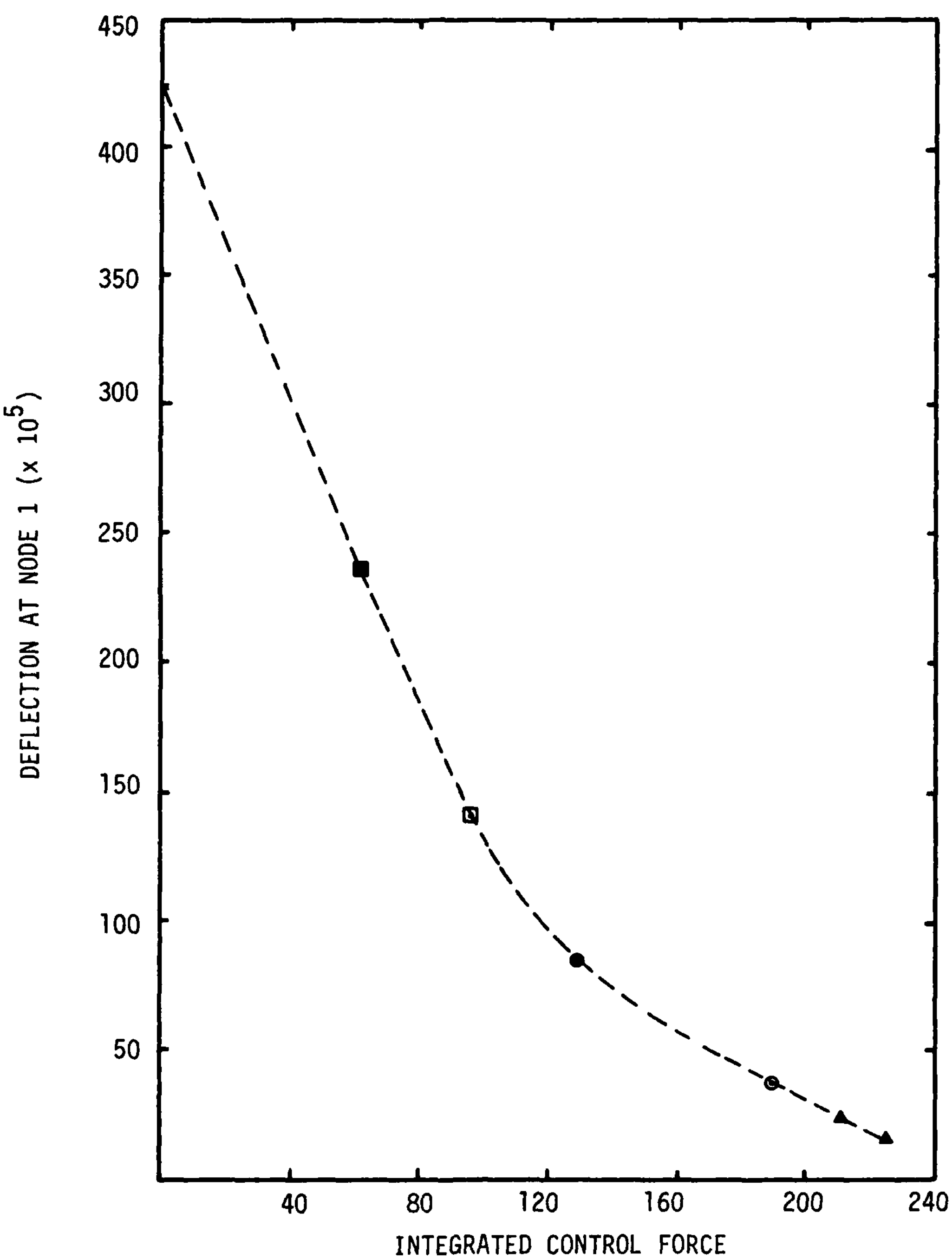


FIGURE 11: INTEGRATED CONTROL FORCE

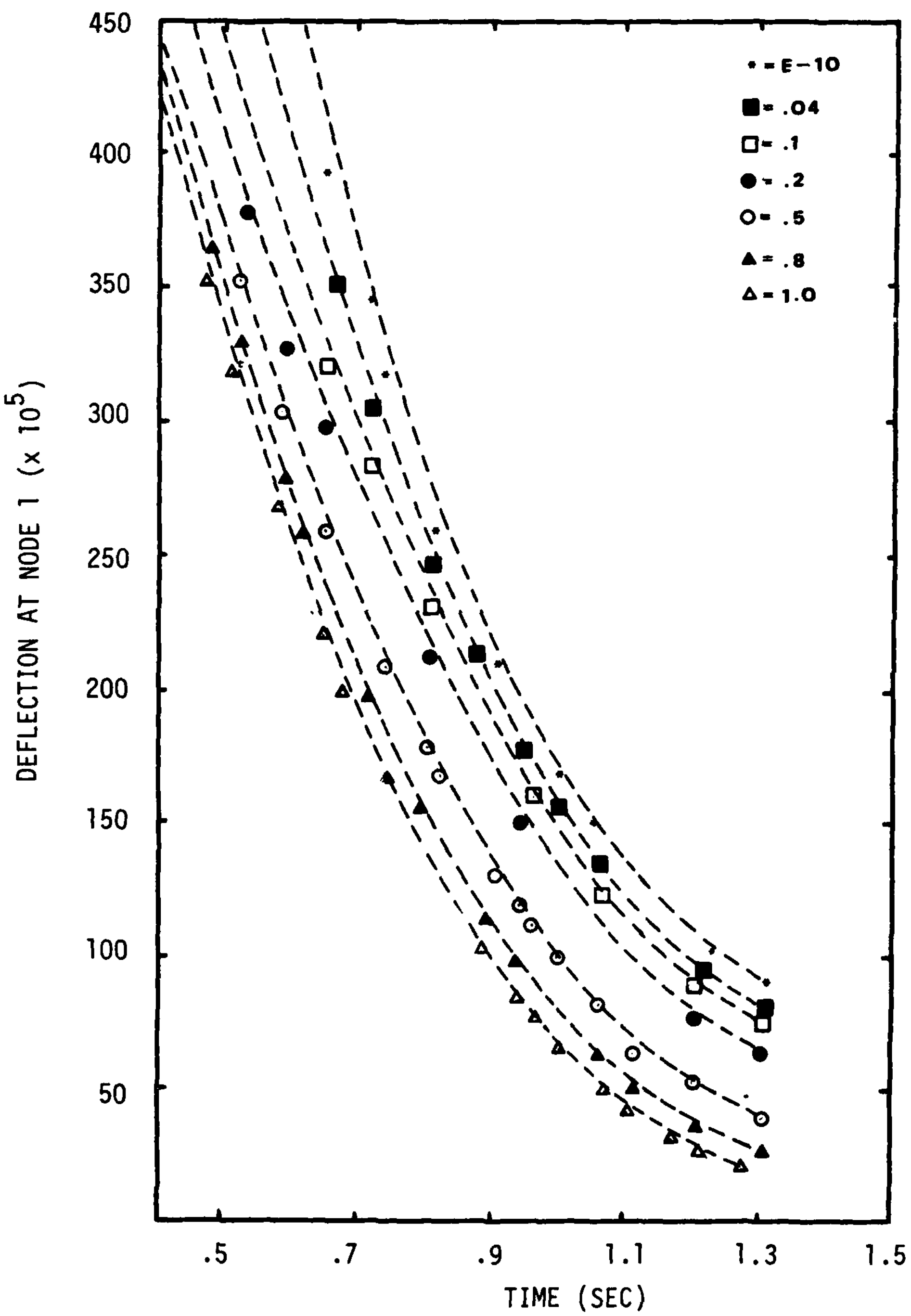


FIGURE 12. CASE IV RESPONSE ENVELOPE WITH Q AS PARAMETER

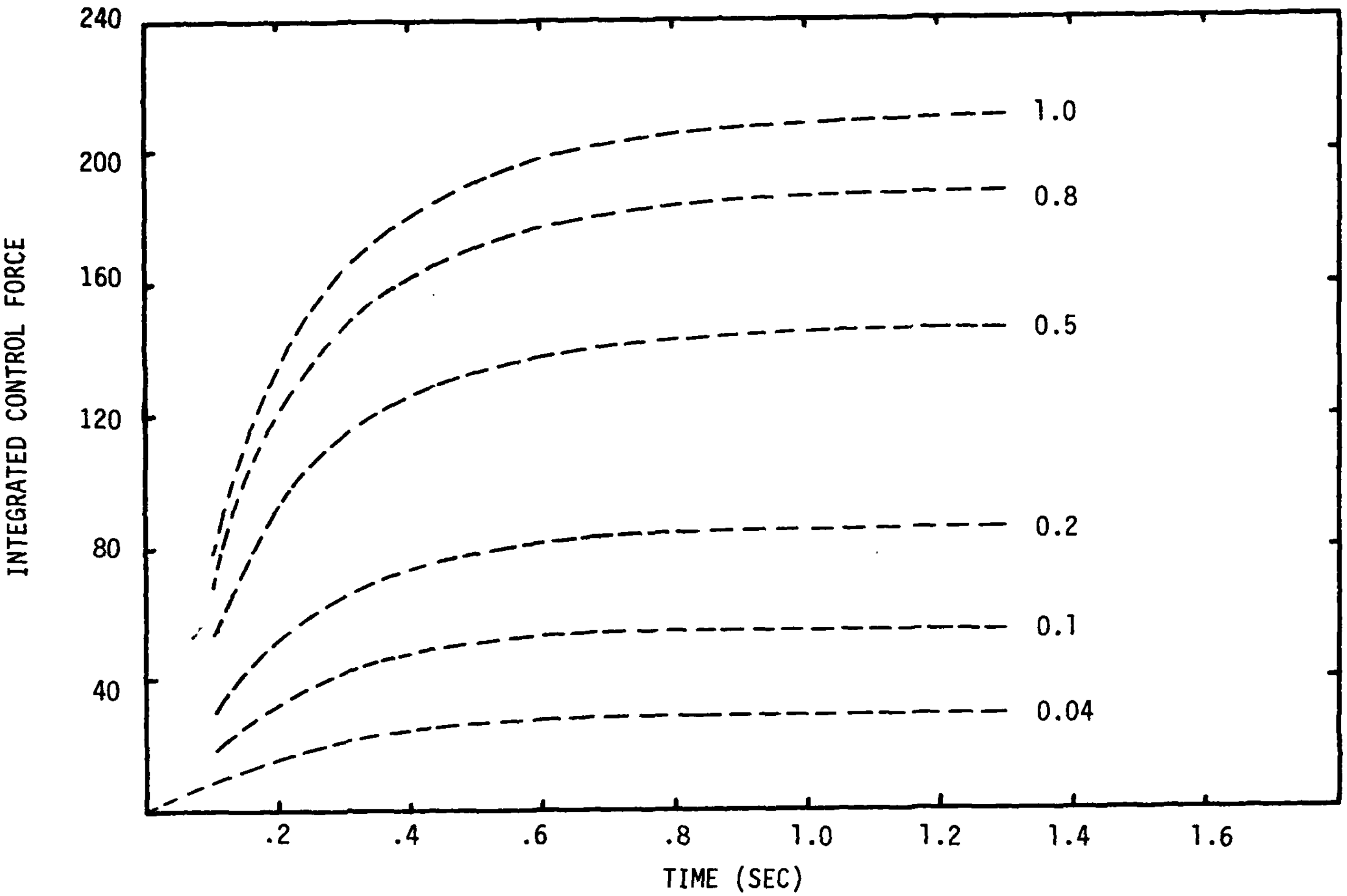


FIGURE 13: CASE IV CONTROL EFFORT WITH Q AS PARAMETER

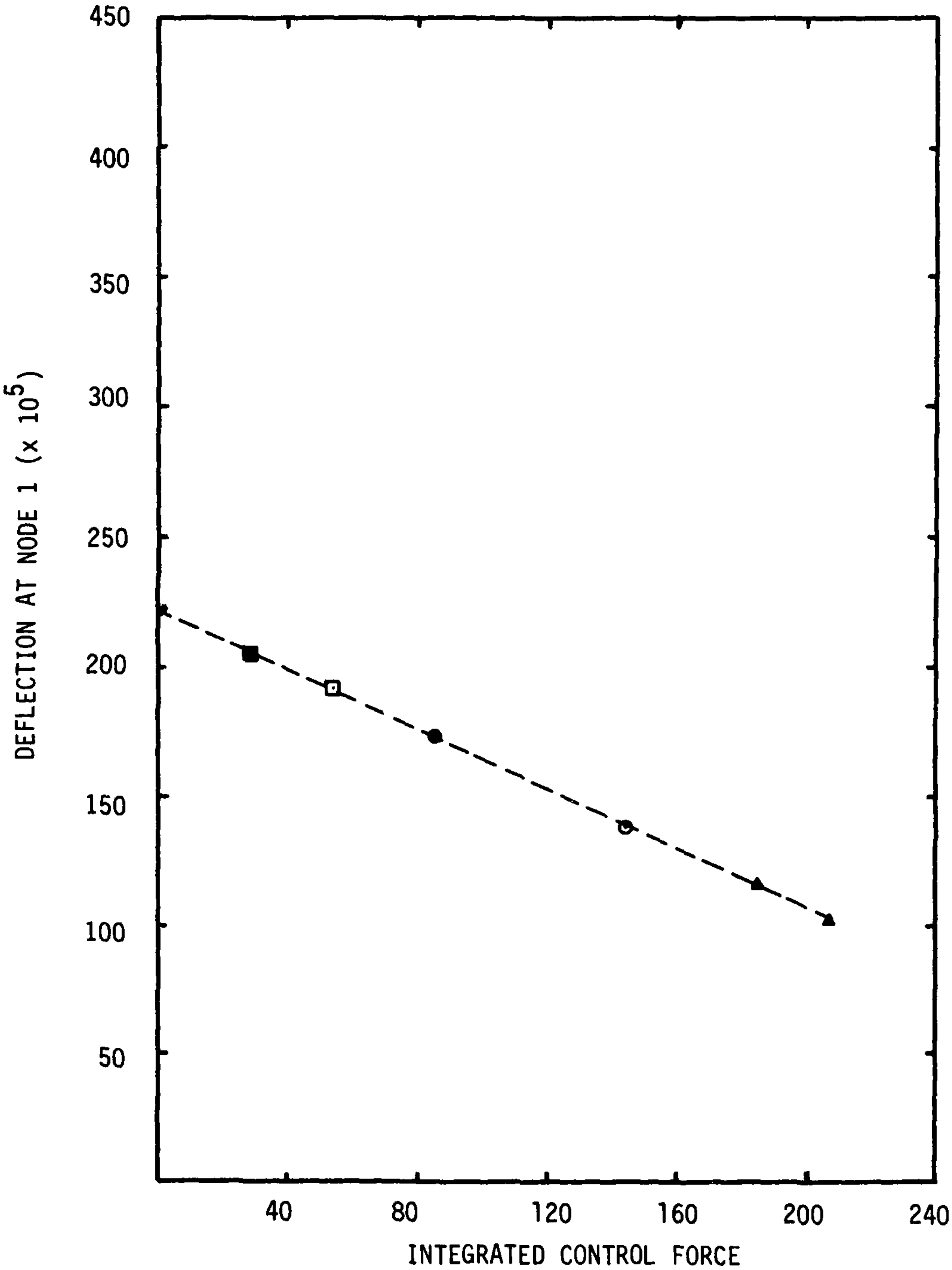


FIGURE 14: CASE IV SYSTEM PERFORMANCE CURVE

70 degrees and Controller 3 had no relative angle less than 60 degrees. Though the spillover terms were significantly reduced and the systems were stable.

The remaining test, Case II, used no transformation. While the individual controllers were designed for asymptotic stability, no effort was made to insure total system stability. Case II did form a stable system, but this cannot be attributed solely to its favorable modal groupings. Case III, using very incompatible groupings, exhibited total system stability before the transformation was performed.

Though each test case had the possibility of major problems, all configurations generated stable controllers that successfully reduced system response. Though triangularization of the system was not achieved in two of the cases where it was attempted, the magnitude of the affected terms were greatly reduced and successful control systems were designed. Simulated response performance curves were found for the four test cases. The performance curves can be compared two ways. A horizontal section taken at the required level of response allows comparison of the system efficiencies by comparison of the expended control effort. Taking a vertical section at the allowable control expenditure allows efficiency comparison by comparison of the achieved responses. The first of these methods will be used in the discussion. This investigation compares two groups of these curves.

The first group consists of Cases I through III. This forms a comparison of three control configurations applied to the nominal design to explore the relationship between the compatibility of the modal groupings and triangularization. Figure 15 presents the performance curves for these three cases. Three results can be seen in Figure 15.

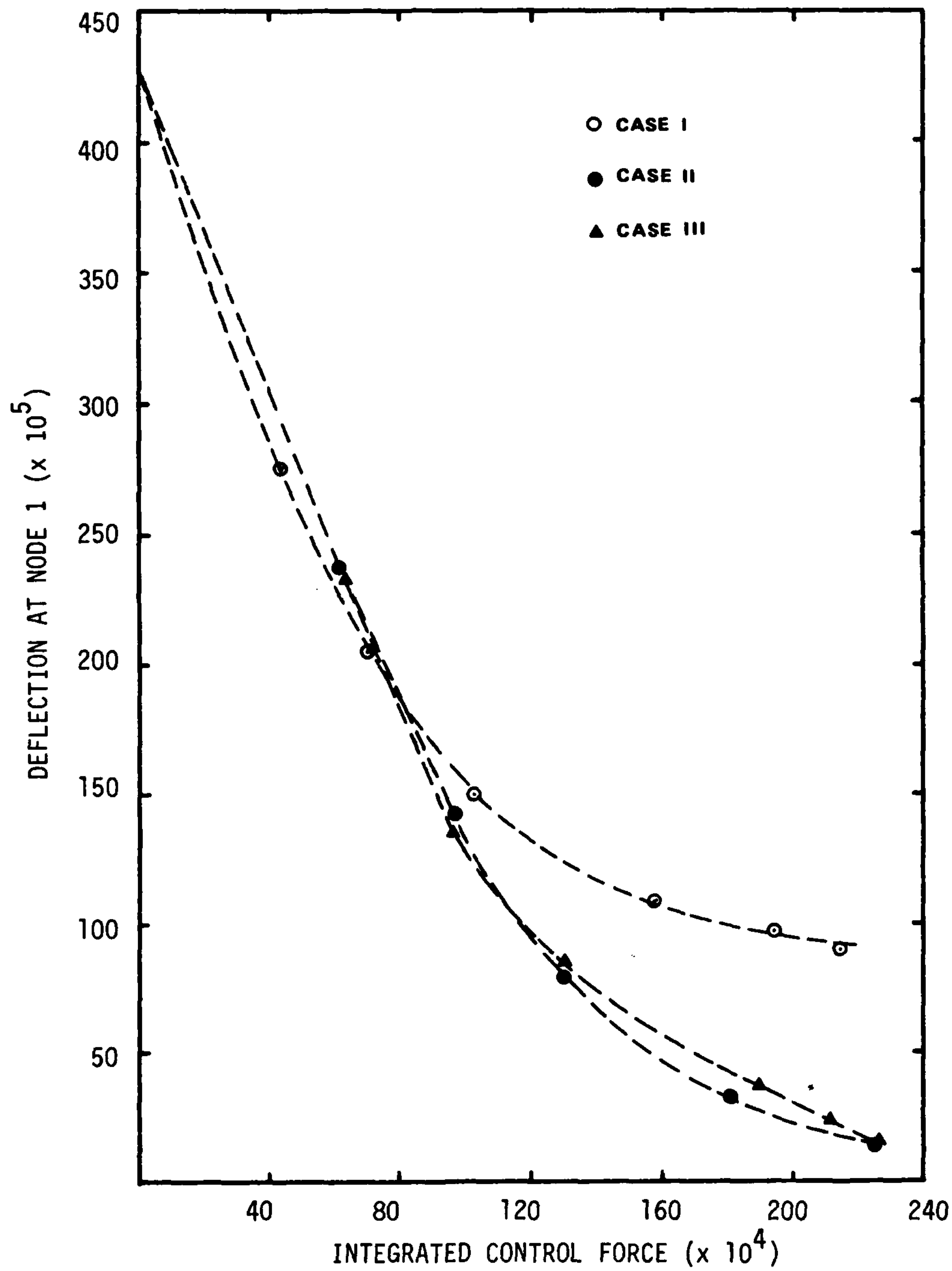


FIGURE 15: COMPARISON OF PERFORMANCE CURVES, CASES I-III

The first is that there is little differentiation between the configurations over a response range covering roughly the upper half of the uncontrolled response. In fact, two configurations are virtually identical over this range. If the difference between Case I and Cases II and III is shown to be significant on more complex models, then the optimum control configuration is shown to depend on the required level of response reduction.

The second result is that triangularization is not desirable if the modal grouping is very compatible. This may be due to the manner in which the transformation attempts to orthogonalize the controllers. It is possible that the transformation may have predetermined orientations for the controllers. In attempting to force this alignment, the natural orthogonality of the favorable grouping is ignored and more control effort is required. This conjecture, though presently unsupported, could explain the worsening of a favorable grouping by the transformation.

Finally, Figure 15 shows the favorable grouping without triangularization to be slightly more efficient than the unfavorable grouping. The inability of the transformation to completely triangularize Case II could account for this difference. Successful triangularization would likely close the gap to some degree. It should be noted that this result depends on the quality of compatible groupings that can be achieved for a given structure. The deflection design demonstrates that even the most favorable groupings can be quite incompatible.

The second investigation is intended to demonstrate comparison of the "controllability" of two structural designs. As implied earlier, this comparison requires the application of the optimum configuration for each

structure. For the investigation, Cases II and IV are used. The previous results show that Case II is the most efficient configuration of those tested. Because the most favorable groupings of the deflection designed structure are so incompatible, the transformation was used in Case IV. While these configurations may well not be optimums for the structures compared, they are the best available within the restrictions of this study. There are several points of interest in Figure 16 which compares the performance curves for Cases II and IV. Two surprises are the linearity of the deflection design curve and the substantial reduction in the uncontrolled response for this case. The linearity of the curve is presently unexplained. The reduction of the uncontrolled response on the deflection design shows the success of the design method. This comparison shows a more clear distinction between low and high levels of response reduction. The greatest possible benefit of the frequency redesign is found in the case where the required response at 0.9 seconds is above or only slightly below its uncontrolled response. In this case, the deflection design would be far superior due to its reduced uncontrolled response.

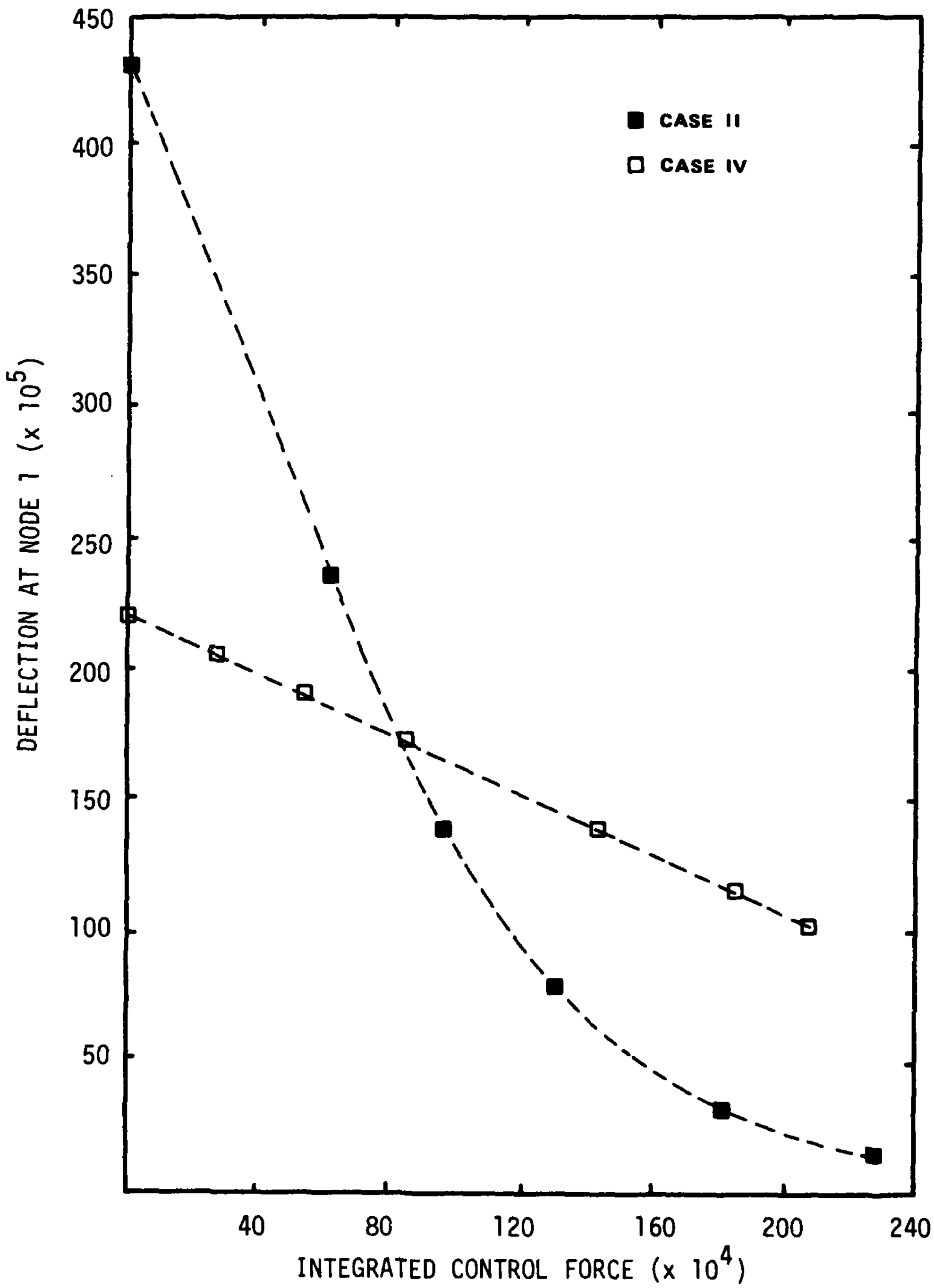


FIGURE 16: COMPARISON OF PERFORMANCE CURVES, CASES II AND IV

VI. CONCLUSIONS

This investigation compared the efficiency of various control system/ structural design configurations. Emphasis was placed on exploration of the conditions governing the loss of system performance in transforming the system to a block traingular form. As expected, the compatibility of the modal groupings proved to be a significant factor. Comparison of controller performance curves for the test cases considered showed that the transformation caused significant loss of system performance when very compatible modal groupings were used. When an extremely incompatible grouping was used, however, the almost triangularized system performance compared favorably with the case representing an untriangularized favorable grouping. The triangularization transformation failed due to the inadequate number of sensors and actuators used. Though the transformation failed to triangularize two test configurations and was not even used on one other, all four configurations generated controllers with total system stability.

Examination of the relative angles in the modal groupings of the frequency designed structure reveals that even the most favorable groupings for this design are very incompatible. The compatibility of the modes could be improved by relocation of the actuators and/or sensors. Additional study is clearly needed to determine the degree of compatibility or incompatibility required for the present assessment of the three control configurations to be valid. Also, a validated characteristic measure of grouping compatibility is needed.

VII. RECOMMENDATIONS

The results of this study have indicated several areas that warrant further exploration. The study showed on the CSDLI that spillover elimination can be detrimental or of benefit to system performance depending on the compatibility of the modal groupings. The generality of this result should, at a minimum, be verified by application to the CSDLII model. Further, testing on more complex models could also show more conclusively the presence or lack of differentiation between the favorable grouping, no transformation and the unfavorable grouping with transformation cases.

Another area of interest is the degree of incompatibility in the modal groupings. A slightly less incompatible unfavorable grouping might allow a more complete elimination of spillover by the transformation. This could eliminate the slight advantage that the favorable grouping with spillover seems to have at this point. One way to improve the "worst case" grouping is to use additional sensors and actuators on all the test cases. As has been noted, the six pair used in this test do not guarantee complete elimination of spillover by the transformation. This lack was evidenced in the unfavorable grouping by the presence of zero and indefinite singular values. The extra observability and controllability would likely be of the most benefit to the unfavorable grouping.

In addition to these ideas, the computer program has a few areas of need that should be mentioned here. At present, the variable lists in the COMMON statements of the program's subroutines are not identical to the lists in the main program. This is believed to be the probable cause

of two significant problems. Matrices formed by modifications in the program are not printed properly by the subroutines PRNT, PRNTXL, and PRNTSM. This has resulted in the use of extra PRINT statements in the program that are not conducive to changes in the order of the control model. Also, subroutine MMUL was found to print erroneous results with no warning. This was corrected by use of the IMSL routine VMULFF in the modifications. It is believed that correction of the COMMON statements will correct these problems and allow use of these subroutines. These routines are very important because their use allows the system order to be changed by altering only the matrix dimension statements. A comment section immediately following the program initializations could also be helpful in adapting the program to a different model. The needed comments would show the matrix dimensions required in terms of system order, the number of modes in each controller, and the number of sensors and actuators. Proper dimensions not only saves core memory, but allows standardized use of the VMULF_ routine which require input of the actual row dimension of the matrices. Also, the needed value of each initialized variable should be described. A program of this size does not warrant a User's Manual, but this sort of description section could be most helpful - especially as the program is successively modified.

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APPENDIX A

NASTRAN ANALYSES

Frequency and Mode Shapes

Nominal Design

$w_1 = 1.342$

$$\phi_1 = \begin{bmatrix} -3.444E-01 \\ 5.964E-01 \\ 1.733E-06 \\ -3.106E-02 \\ 5.378E-02 \\ -1.089E-05 \\ -5.079E-02 \\ 6.517E-02 \\ 6.379E-02 \\ -3.106E-02 \\ 7.656E-02 \\ 6.378E-02 \end{bmatrix}$$

$w_2 = 1.665$

$$\phi_2 = \begin{bmatrix} -5.428E-01 \\ -3.135E-01 \\ 1.990E-01 \\ -1.263E-01 \\ -7.294E-02 \\ -9.754E-02 \\ -1.097E-01 \\ -4.164E-02 \\ 6.727E-02 \\ -0.092E-02 \\ -7.422E-02 \\ 6.728E-02 \end{bmatrix}$$

$w_3 = 2.891$

$$\phi_3 = \begin{bmatrix} 4.921E-02 \\ 2.843E-02 \\ -3.787E-01 \\ -3.124E-01 \\ -1.805E-01 \\ -6.518E-02 \\ -2.726E-01 \\ -1.274E-01 \\ -1.371E-01 \\ -2.465E-01 \\ -1.726E-01 \\ -1.371E-01 \end{bmatrix}$$

$w_4 = 2.957$

$$\phi_4 = \begin{bmatrix} 5.725E-02 \\ -9.915E-02 \\ -1.448E-04 \\ -1.759E-01 \\ 3.045E-01 \\ -7.108E-05 \\ -2.387E-01 \\ 3.408E-01 \\ -9.157E-02 \\ -1.759E-01 \\ 3.771E-01 \\ 9.148E-02 \end{bmatrix}$$

$w_5 = 3.398$

$$\phi_5 = \begin{bmatrix} -1.369E-01 \\ 7.907E-02 \\ 3.440E-01 \\ -1.620E-01 \\ -9.355E-02 \\ 4.968E-01 \\ -1.620E-01 \\ -7.310E-02 \\ 7.578E-02 \\ -1.443E-01 \\ -1.036E-01 \\ 7.577E-02 \end{bmatrix}$$

$w_6 = 4.204$

$$\phi_6 = \begin{bmatrix} 2.975E-05 \\ -5.416E-06 \\ 7.306E-07 \\ -2.041E-01 \\ 3.535E-01 \\ 5.599E-06 \\ -2.041E-01 \\ -3.535E-01 \\ 1.247E-04 \\ 4.082E-01 \\ 2.943E-06 \\ -2.833E-05 \end{bmatrix}$$

$w_7 = 4.660$

$$\phi_7 = \begin{bmatrix} 5.570E-02 \\ -9.646E-02 \\ -1.218E-05 \\ -3.438E-02 \\ 5.957E-02 \\ -2.359E-05 \\ -2.880E-02 \\ 5.645E-02 \\ 4.873E-01 \\ -3.448E-02 \\ 5.318E-02 \\ -4.871E-01 \end{bmatrix}$$

$w_8 = 4.755$

$$\phi_8 = \begin{bmatrix} -7.581E-02 \\ -4.378E-02 \\ 1.837E-01 \\ 4.696E-02 \\ 2.721E-02 \\ 9.788E-02 \\ 3.677E-02 \\ 3.243E-02 \\ -4.696E-01 \\ 4.650E-02 \\ 1.559E-02 \\ -4.697E-01 \end{bmatrix}$$

$w_9 = 8.539$

$$\phi_9 = \begin{bmatrix} 1.445E-01 \\ 8.346E-02 \\ 2.702E-01 \\ 2.125E-01 \\ 1.227E-01 \\ -3.266E-01 \\ -1.413E-01 \\ -3.096E-01 \\ -1.503E-02 \\ -3.389E-01 \\ -3.227E-02 \\ -1.502E-02 \end{bmatrix}$$

$w_{10} = 9.251$

$$\phi_{10} = \begin{bmatrix} 5.773E-03 \\ -9.966E-03 \\ 5.299E-05 \\ 2.242E-01 \\ -3.882E-01 \\ -4.343E-05 \\ -3.846E-01 \\ -3.681E-02 \\ 1.180E-02 \\ 2.241E-01 \\ 3.147E-01 \\ -1.189E-02 \end{bmatrix}$$

$w_{11} = 10.285$

$$\phi_{11} = \begin{bmatrix} 1.594E-01 \\ 9.204E-02 \\ 2.580E-01 \\ -1.516E-01 \\ -8.758E-02 \\ -3.116E-01 \\ -1.619E-01 \\ 3.311E-01 \\ 9.166E-04 \\ 2.057E-01 \\ -3.057E-01 \\ 9.186E-04 \end{bmatrix}$$

$w_{12} = 12.905$

$$\phi_{12} = \begin{bmatrix} 8.373E-02 \\ 4.834E-02 \\ 1.586E-01 \\ -4.058E-01 \\ -2.343E-01 \\ -1.610E-01 \\ 2.995E-01 \\ -1.419E-01 \\ -8.204E-03 \\ 2.687E-02 \\ 3.304E-01 \\ -8.208E-03 \end{bmatrix}$$

Frequency and Mode Shapes

Deflection Design

$w_1 = 1.271$

$$\phi_1 = \begin{bmatrix} -5.705E-01 \\ 3.665E-01 \\ 1.768E-01 \\ -3.655E-02 \\ -1.308E-02 \\ -4.537E-03 \\ -5.473E-02 \\ 3.613E-02 \\ 1.210E-02 \\ -2.437E-02 \\ 4.138E-02 \\ -2.242E-02 \end{bmatrix}$$

$w_2 = 2.783$

$$\phi_2 = \begin{bmatrix} -3.157E-01 \\ -5.282E-01 \\ 1.657E-01 \\ -0.296E-02 \\ -7.686E-02 \\ -2.471E-02 \\ 7.065E-02 \\ -1.012E-01 \\ -1.127E-02 \\ 4.452E-02 \\ -2.290E-01 \\ 9.375E-02 \end{bmatrix}$$

$w_3 = 3.291$

$$\phi_3 = \begin{bmatrix} 7.896E-02 \\ 1.209E-01 \\ 3.032E-01 \\ 3.745E-01 \\ 1.831E-01 \\ 2.748E-02 \\ 3.420E-01 \\ -1.528E-01 \\ 2.327E-02 \\ 1.928E-01 \\ -1.161E-01 \\ 1.448E-01 \end{bmatrix}$$

w_4 4.668

$$\phi_4 = \begin{bmatrix} -4.664E-02 \\ -1.780E-01 \\ 1.021E-01 \\ 9.159E-02 \\ 1.450E-01 \\ -3.881E-02 \\ -1.839E-01 \\ 1.911E-01 \\ 2.382E-02 \\ 2.166E-01 \\ 4.800E-01 \\ 2.763E-01 \end{bmatrix}$$

$w_5 = 6.783$

$$\phi_5 = \begin{bmatrix} 1.476E-01 \\ -7.105E-02 \\ 4.796E-01 \\ 7.732E-02 \\ 2.230E-02 \\ 1.466E-01 \\ -2.198E-01 \\ 1.749E-01 \\ 2.608E-02 \\ -3.183E-01 \\ -3.035E-02 \\ -1.824E-01 \end{bmatrix}$$

$w_6 = 7.095$

$$\phi_6 = \begin{bmatrix} 1.688E-01 \\ 1.644E-01 \\ 2.013E-01 \\ -3.045E-01 \\ -2.392E-01 \\ 2.046E-01 \\ -1.752E-01 \\ -1.080E-01 \\ -9.479E-02 \\ 2.448E-01 \\ -1.179E-01 \\ 2.945E-01 \end{bmatrix}$$

$w_7 = 9.040$

$$\phi_7 = \begin{bmatrix} 1.897E-02 \\ -2.408E-03 \\ 2.658E-02 \\ -1.146E-01 \\ -2.583E-01 \\ 1.415E-01 \\ 3.308E-01 \\ 2.413E-01 \\ 4.681E-01 \\ -2.105E-02 \\ 1.008E-01 \\ 3.942E-02 \end{bmatrix}$$

$w_8 = 10.252$

$$\phi_8 = \begin{bmatrix} 1.695E-02 \\ 5.644E-02 \\ -7.277E-02 \\ 5.334E-03 \\ 2.474E-01 \\ -1.846E-01 \\ -2.584E-01 \\ 1.881E-01 \\ 3.524E-01 \\ 7.131E-02 \\ -3.707E-01 \\ 1.641E-01 \end{bmatrix}$$

$w_9 = 11.590$

$$\phi_9 = \begin{bmatrix} 6.067E-02 \\ -7.203E-03 \\ 1.613E-01 \\ -3.816E-01 \\ 3.213E-01 \\ -8.926E-02 \\ 5.765E-02 \\ -2.472E-01 \\ 1.849E-01 \\ 1.436E-01 \\ 1.407E-01 \\ -2.724E-01 \end{bmatrix}$$

$w_{10} = 12.030$

$$\phi_{10} = \begin{bmatrix} 4.540E-02 \\ 5.311E-02 \\ 4.961E-02 \\ -2.689E-01 \\ 2.101E-01 \\ -1.573E-01 \\ 2.480E-01 \\ 1.285E-01 \\ -1.935E-01 \\ -3.494E-01 \\ 5.627E-03 \\ 3.373E-01 \end{bmatrix}$$

$w_{11} = 12.608$

$$\phi_{11} = \begin{bmatrix} -9.773E-03 \\ 4.632E-03 \\ -3.859E-02 \\ 1.025E-01 \\ -5.987E-02 \\ 4.975E-03 \\ -1.449E-01 \\ -4.635E-01 \\ 2.718E-01 \\ -3.196E-01 \\ 1.331E-01 \\ 2.336E-01 \end{bmatrix}$$

$w_{12} = 13.908$

$$\phi_{12} = \begin{bmatrix} 9.764E-02 \\ 4.486E-02 \\ 1.796E-01 \\ 3.036E-02 \\ -3.203E-01 \\ -5.889E-01 \\ -5.736E-03 \\ -1.148E-02 \\ 1.506E-03 \\ 4.034E-02 \\ 4.242E-02 \\ -4.708E-02 \end{bmatrix}$$

CSDLI D MATRIX

(Also C^T for Collocated Actuators/Sensors)

	Actuators/Sensors					
Mode	1	2	3	4	5	6
1	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0
4	.3536	-.3536	0.0	0.0	0.0	0.0
5	-.6124	.6124	0.0	0.0	0.0	0.0
6	.7071	.7071	0.0	0.0	0.0	0.0
7	0.0	0.0	.3536	-.3536	0.0	0.0
8	0.0	0.0	.6124	-.6124	0.0	0.0
9	0.0	0.0	.7071	.7071	0.0	0.0
10	0.0	0.0	0.0	0.0	-.7071	.7071
11	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	.7071	.7071

APPENDIX B

PROGRAM MODIFICATIONS AND TYPICAL DATA FILE

```
      PROGRAM ACOSSCF(INPUT,OUTPUT,TAPE8,TAPE6)
C
C      PFN:  ACOSSCF
C  THIS PROGRAM GENERATES A LOWER TRIANGULAR TRANSFORMATION
C  THE THREE CONTROLLER SOLUTION MAY INCLUDE RESIDUALS.
C
      REAL A1(12,12),A2(12,12),A3(12,12),A4(12,12)
      REAL B1(12,12),B2(12,12),B3(12,12),B4(12,12)
      REAL C1(12,12),C2(12,12),C3(12,12),C4(12,12)
      REAL CTCC1(12,12),CTCC2(12,12),CTCC3(12,12),CTCC4(12,12)
      REAL SAT(12,12),SAT2(12,12),SAT3(12,12),SAT4(12,12)
      REAL AKC(12,12),ACT(12,12),BCG(12,12),KCC(12,12)
      REAL P(12,12),S(12,12)
      REAL QA1(12,12),QA2(12,12),QA3(12,12),QA4(12,12)
      REAL XHAT(2,48),PETA(21,48),CV(2,21),XLOS(2)
      REAL ACG1(12,12),ACG2(12,12),ACG3(12,12),ACG4(12,12)
      REAL ABG1(12,12),ABG2(12,12),ABG3(12,12),ABG4(12,12)
      REAL GAIN1(12,12),GAIN2(12,12),GAIN3(12,12),GAIN4(12,12)
      REAL KT1(12,12),KT2(12,12),KT3(12,12),KT4(12,12)
      REAL KOB1(12,12),KOB2(12,12),KOB3(12,12),KOB4(12,12)
      REAL GAMMA1(12,12),GAMMA2(12,12),GAMMA3(12,12)
      REAL T2(12,12),T3(12,12),T4(12,12),BB(17)
      REAL TRT(12,12),TEN(12,12),CT(12,12),V(12,12)
      REAL RK(12,12),RK1(12,12),RK2(12,12),RK3(12,12)
      REAL RG2(12,12),RG3(12,12),RG4(12,12)
      REAL MAJM(48,48),D(17),W(17),TOL,DT,X0(48)
      REAL ZETA,CLOS(2,12),SING(12),XTR(12,12),X1(48)
      REAL EAT(48,48),EAT2(48,48),WORK(48,48),STOR(12,12)
      REAL PHIA(12,12),PHIS(12,12),MODE(2,12),INIT(4,12)
      REAL PXHT(24,48),GPART(6,24),UHAT(6,48),SCALEB
      REAL U1(6),UBAR(6),TEFF(6),DUM1(12),DUM2(6),DUM3(6)
      REAL PHI(12,12),DMAT(12,12),CMAT(12,12),NEWCON
      REAL KFIRST(12,12),KREAL(12,12)
      REAL PHI1(12,6),PHI2(12,6),PHI3(12,6),PHI4(12,6)
      REAL PHINEW(12,12),GNIT(4,12),DUM4(12,12),DUM6(6)
      REAL CDOT,MAGI,CANG,PHIT(12,12),DUM5(24)
      INTEGER N,N2,NC1,NC2,NC3,NC12,NC22,NC32,NR,NR2,NMODE
      INTEGER IC1(12),IC2(12),IC3(12),I,J,K,L,M,KK,LL,MM
      INTEGER DEC,Q,NACT,NSEN,IR(12),IER,SKIP,NCOL,NCOL1,NMOD2
      INTEGER NDA,NDIM,NDA1,NDIM1,ZZ,E2,E3,E4,P1,P2,P3,AA
      INTEGER INCOND
      COMPLEX Z(24),W1(12)
      COMMON/MAINA/NDA,NDA1
      COMMON/MAINB/NCOL,NCOL1
      COMMON/MAIN1/NDIM,NDIM1,TEN,X(2304)
      COMMON/MAIN2/STOR
      COMMON/MAIN3/XTR
      COMMON/SAVE/T(100),TS(100)
      COMMON/INOUT/KOUT,TAPE
      COMMON/NUM/IC1,IC2,IC3,IR,NC1,NC2,NC3,NR
C
C
C  INITIALIZATIONS
C
```

```
      PROGRAM ACOSSCF(INPUT,OUTPUT,TAPE8,TAPE6)
C
C     PFN:  ACOSSCF
C  THIS PROGRAM GENERATES A LOWER TRIANGULAR TRANSFORMATION
C  THE THREE CONTROLLER SOLUTION MAY INCLUDE RESIDUALS.
C
      REAL A1(12,12),A2(12,12),A3(12,12),A4(12,12)
      REAL B1(12,12),B2(12,12),B3(12,12),B4(12,12)
      REAL C1(12,12),C2(12,12),C3(12,12),C4(12,12)
      REAL CTCC1(12,12),CTCC2(12,12),CTCC3(12,12),CTCC4(12,12)
      REAL SAT(12,12),SAT2(12,12),SAT3(12,12),SAT4(12,12)
      REAL AKC(12,12),ACT(12,12),BCG(12,12),KCC(12,12)
      REAL P(12,12),S(12,12)
      REAL QA1(12,12),QA2(12,12),QA3(12,12),QA4(12,12)
      REAL XHAT(2,48),PETA(21,48),CV(2,21),XLOS(2)
      REAL ACG1(12,12),ACG2(12,12),ACG3(12,12),ACG4(12,12)
      REAL ABG1(12,12),ABG2(12,12),ABG3(12,12),ABG4(12,12)
      REAL GAIN1(12,12),GAIN2(12,12),GAIN3(12,12),GAIN4(12,12)
      REAL KT1(12,12),KT2(12,12),KT3(12,12),KT4(12,12)
      REAL KOB1(12,12),KOB2(12,12),KOB3(12,12),KOB4(12,12)
      REAL GAMMA1(12,12),GAMMA2(12,12),GAMMA3(12,12)
      REAL T2(12,12),T3(12,12),T4(12,12),BB(17)
      REAL TRT(12,12),TEN(12,12),CT(12,12),V(12,12)
      REAL RK(12,12),RK1(12,12),RK2(12,12),RK3(12,12)
      REAL RG2(12,12),RG3(12,12),RG4(12,12)
      REAL MAJM(48,48),D(17),W(17),TOL,DT,X0(48)
      REAL ZETA,CLOS(2,12),SING(12),XTR(12,12),X1(48)
      REAL EAT(48,48),EAT2(48,48),WORK(48,48),STOR(12,12)
      REAL PHIA(12,12),PHIS(12,12),MODE(2,12),INIT(4,12)
      REAL PXHT(24,48),GPART(6,24),UHAT(6,48),SCALEB
      REAL U1(6),UBAR(6),TEFF(6),DUM1(12),DUM2(6),DUM3(6)
      REAL PHI(12,12),DMAT(12,12),CMAT(12,12),NEWCON
      REAL KFIRST(12,12),KREAL(12,12)
      REAL PHI1(12,6),PHI2(12,6),PHI3(12,6),PHI4(12,6)
      REAL PHINEW(12,12),GNIT(4,12),DUM4(12,12),DUM6(6)
      REAL CDOT,MAGI,CANG,PHIT(12,12),DUM5(24)
      INTEGER N,N2,NC1,NC2,NC3,NC12,NC22,NC32,NR,NR2,NMODE
      INTEGER IC1(12),IC2(12),IC3(12),I,J,K,L,M,KK,LL,MM
      INTEGER DEC,Q,NACT,NSEN,IR(12),IER,SKIP,NCOL,NCOL1,NMOD2
      INTEGER NDA,NDIM,NDA1,NDIM1,ZZ,E2,E3,E4,P1,P2,P3,AA
      INTEGER INCOND
      COMPLEX Z(24),W1(12)
      COMMON/MAINA/NDA,NDA1
      COMMON/MAINB/NCOL,NCOL1
      COMMON/MAIN1/NDIM,NDIM1,TEN,X(2304)
      COMMON/MAIN2/STOR
      COMMON/MAIN3/XTR
      COMMON/SAVE/T(100),TS(100)
      COMMON/INOUT/KOUT,TAPE
      COMMON/NUM/IC1,IC2,IC3,IR,NC1,NC2,NC3,NR
C
C
C  INITIALIZATIONS
C
```

```
C  INITIALIZATIONS
C   .
C
C  ******************
C  ******************
      READ(8,*) SCALEB
C  ******************
C  ******************
C
      NDIM = 12
      NDIM1 = 13
      NCOL = 12
      NCOL1 = 13
      NMOD2 = 24
      NDA = 48
      NDA1 = 49
      KOUT = 6
      TAPE = 9
      Q = 0
      IER = 0
      ZZ = 0
      AA = 0
C
C
      PRINT'(////)'
      PRINT*,'     ******************************************* '
      PRINT*,'     *****                                 ***** '
      PRINT*,'     *****   3 4 L O W E R - R E S I D U A L   ***** '
      PRINT*,'     *****            B L O C K              ***** '
      PRINT*,'     *****          C S D L   I I            ***** '
      PRINT*,'     *****                                 ***** '
      PRINT*,'     *****       CONTROL FORCE MODIFIED     *****'
      PRINT*,'     *****                                 *****'
      PRINT*,'     ******************************************* '
      PRINT'(//)'
      PRINT*,'  THIS PROGRAM GENERATES A SOLUTION',
     *        ' USING A LOWER TRIANGULAR TRANSFORMATION '
      PRINT'(////)'
C
C
C
C
C
C
C  INITIAL SELECTION FOR THREE OR FOUR CONTROLLERS
C
C
??
```

```
C  PHI MATRICES AND CONTROLLER ENTRIES
C
C
      PRINT'(///)'
      IF (DEC.EQ.3) THEN
      PRINT*,' ENTER NC1,NC2,NC3,NR,NACT,NSEN,ZETA  >'
      ELSE
      PRINT*,' ENTER NC1,NC2,NC3,NC4,NACT,NSEN,ZETA  >'
      ENDIF
      READ(8,*) NC1,NC2,NC3,NR,NACT,NSEN,ZETA
      PRINT*,NC1,NC2,NC3,NR,NACT,NSEN,ZETA
      PRINT*,' '
      N = NC1 + NC2 + NC3 + NR
C READ PHI MATRIX BY COLUMNS
      PRINT'(/)'
      DO 1 J=1,N
      READ(8,*)(PHI(I,J),I=1,N)
      PRINT*,'MODE SHAPE ',J,' IS>'
      PRINT*,'    ',(PHI(I,J),I=1,N)
    1 CONTINUE
      PRINT'(//)'
C READ THE D MATRIX BY ROWS
      PRINT*,'THE D MATRIX IS'
      PRINT'(/)'
      DO 2 I=1,N
      READ(8,*) (DMAT(I,J),J=1,NACT)
      PRINT'(1X,12F10.4)',(DMAT(I,J),J=1,NACT)
    2 CONTINUE
      PRINT'(//)'
C  READ CMAT TRANSPOSED BY ROWS
      PRINT*,'THE C MATRIX TRANSPOSED IS'
      PRINT'(/)'
      DO 3 I=1,N
      READ(8,*) (CMAT(I,J),J=1,NSEN)
      PRINT'(1X,12F10.4)',(CMAT(I,J),J=1,NSEN)
    3 CONTINUE
      PRINT'(//)'
C
C
C  NOW COMPUTE PHIA AND PHIS (PHI[TR]*D AND C*PHI)
      CALL VMULFM(PHI,DMAT,N,N,NACT,NCOL,NCOL,PHIA,NCOL,IER)
      PRINT*,'THE PHIA MATRIX IS'
      CALL PRNT(PHIA,N,NACT)
      CALL TANGL(PHIA,N,NACT,DUM1,DUM4)
      PRINT'(//)'
      CALL VMULFM(PHI,CMAT,N,N,NSEN,NCOL,NCOL,PHIS,NCOL,IER)
      PRINT*,'THE PHIS MATRIX IS'
      PRINT'(/)'
      CALL PRNT(PHIS,N,NSEN)
      PRINT'(//)'
C
C
C  OMEGAS
C
```

```
C  INITIAL CONDITIONS
C  THESE ARE READ IN ONLY ONCE FOR EACH JOB,
C  REGARDLESS OF THE NUMBER OF CONSECUTIVE RUNS
C
C  REMEMBER --  EVEN THOUGH RESIDUAL MODES DO NOT HAVE E AND
C  E DOT TERMS, THIS READ STATEMENT WILL BE LOOKING FOR THEM,
C  SO INPUT E AND E DOT TERMS FOR THE RESIDUALS ALSO.
C  DON'T WORRY -- SUBROUTINE FORMXO WILL FILTER THEM OUT LATER.
C
C  INCOND = 0 IF INITIAL CONDITIONS ARE IN PHYSICAL VARIABLES
C  INCOND = 1 IF INITIAL CONDITIONS ARE IN MODAL COORDINATES

C********************
      INCOND = 1
C*******************
C
      IF(AA.EQ.0) THEN
      PRINT*,' ENTER THE INITIAL CONDITIONS FOR ',N,' MODES '
      IF (INCOND.EQ.0) THEN
      PRINT*,'    CALL THE PHYSICAL VARIABLE "G" '
      PRINT*,'THEN ROW1=G, ROW2=G DOT, ROW3=E, ROW4=E DOT'
      DO 80 I=1,4
      READ(8,*) (GNIT(I,J),J=1,N)
      PRINT'(1X,12F10.8)',(GNIT(I,J),J=1,N)
   80 CONTINUE
      CALL TFR(PHIT,PHI,N,N,1,2)
      CALL LINV3F(PHIT,DUM1,1,N,N,-1,D2,DUM5,IER)
      CALL VMULFF(GNIT,PHIT,4,N,N,4,N,INIT,4,IER)
      PRINT'(/)'
      PRINT*,'  INITIAL CONDITIONS IN MODAL COORDINATES ARE '
      DO 81 I=1,4
      PRINT'(1X,12F10.7)',(INIT(I,J),J=1,N)
   81 CONTINUE
      ELSE
      PRINT*,' ROW1=ETA, ROW2=ETA DOT, ROW3=E, ROW4=E DOT '
      PRINT*,'NOTE....INPUT IS IN MODAL COORDINATES!'
      DO 90 I=1,4
      READ(8,*) (INIT(I,J),J=1,N)
   90 CONTINUE
      CALL VMULFF(INIT,PHI,4,N,N,4,N,GNIT,4,IER)
      PRINT'(///)'
      PRINT*,'INITIAL CONDITIONS IN PHYSICAL VARIABLES ARE'
      DO 94 I=1,4
   94 PRINT'(1X,12F10.8)',(GNIT(I,J),J=1,N)
      ENDIF
      PRINT'(//)'
      PRINT*,' THE INITIAL CONDITIONS,(XO AT T=0), ARE '
      CALL FORMXO(XO,INIT,DEC)
      CALL PRNT(XO,M,1)
      AA = 1
      ENDIF
  100 CONTINUE
      PRINT*,' TO PRINT ALL OF THE MATRICES ENTER 1, ELSE ENTER 0
      READ(8,*) Q
```

```
C  READ IN THE WEIGHTING MATRIX DIAGONAL VALUES
C   .
C
C  NOTE: THE INPUT VALUES ARE FOR THE PURPOSE OF SETTING
C  ONLY THE RELATIVE MAGNITUDE OF WEIGHTING OF THE MODES.
C  THESE ARE THEN SCALEBD BY THE VARIABLE 'SCALEB'.
C
C
      PRINT*,' ENTER THE DIAGONAL VALUES OF QOB '
      PRINT*,' '
      PRINT*,' NOTE: THESE VALUES WILL BE SCALED BY THE VALUE '
      PRINT*,' OF 'SCALEB' SET IN THE PROGRAM INITIALIZATIONS '
      READ(8,*) (BB(I),I=1,N)
      PRINT*,' '
      PRINT*,(BB(I),I=1,N)
      DO 106 I=1,N
 106  BB(I)=BB(I)*SCALEB
      PRINT*,' '
      PRINT*,'WEIGHTING MATRIX IS MULT BY SCALE = ',SCALEB
      PRINT'(///)'
C
C
C  FORMING THE A,B,C AND WEIGHTING MATRICES
C
C
      CALL FORMA(A1,D,W,NC1,NC12,IC1)
      CALL FORMB(B1,PHIA,NC1,NC12,NACT,IC1)
      CALL FORMC(C1,PHIS,NC1,NC12,NSEN,IC1)
      CALL FORMPHI(PHI1,PHI,N,NC1,IC1)
      CALL FORMA(A2,D,W,NC2,NC22,IC2)
      CALL FORMB(B2,PHIA,NC2,NC22,NACT,IC2)
      CALL FORMC(C2,PHIS,NC2,NC22,NSEN,IC2)
      CALL FORMPHI(PHI2,PHI,N,NC2,IC2)
      CALL FORMA(A3,D,W,NC3,NC32,IC3)
      CALL FORMB(B3,PHIA,NC3,NC32,NACT,IC3)
      CALL FORMC(C3,PHIS,NC3,NC32,NSEN,IC3)
      CALL FORMPHI(PHI3,PHI,N,NC3,IC3)
      CALL FORMA(A4,D,W,NR,NR2,IR)
      CALL FORMB(B4,PHIA,NR,NR2,NACT,IR)
      CALL FORMC(C4,PHIS,NR,NR2,NSEN,IR)
      CALL FORMPHI(PHI4,PHI,N,NR,IR)
      CALL FORMQ1(QA1,BB,NC1,IC1)
      CALL FORMQ1(QA2,BB,NC2,IC2)
      CALL FORMQ1(QA3,BB,NC3,IC3)
      IF (DEC.EQ.4) THEN
      CALL FORMQ1(QA4,BB,NR,IR)
      ENDIF
C
C
C  PRINTING THE A,B,C AND WEIGHTING MATRICES
```

```
C  EAT2 IS NOW THE SOLUTION TO E TO THE AT
C  WE NOW PROPAGATE THE E TO THE AT MATRIX IN HALF MINUTE STEPS
C
C  FIRST GENERATE THE [C1:C2:C3] MATRIX
C
C
      DO 260 I=1,NSEN
      DO 260 J=1,NC1
 260  V(I,J)=C1(I,J)
      DO 270 I=1,NSEN
      DO 270 J=1,NC2
 270  V(I,J+NC1)=C2(I,J)
      DO 280 I=1,NSEN
      DO 280 J=1,NC3
 280  V(I,J+NC1+NC2)=C3(I,J)
      NMODE=NC1+NC2+NC3
      IF (NR.GT.0) THEN
      DO 290 I=1,NSEN
      DO 290 J=1,NR
 290  V(I,J+NMODE)=C4(I,J)
      NMODE=NMODE+NR
      ENDIF
C
      PRINT*,' THE C PARTITION MATRIX IS '
      CALL PRNT(V,NSEN,NMODE)
C
C  NOW GENERATE THE [PHI1:PHI2:PHI3] MATRIX
C
      DO 282 I=1,N
      DO 282 J=1,NC1
 282  PHINEW(I,J)=PHI1(I,J)
      DO 284 I=1,N
      DO 284 J=1,NC2
 284  PHINEW(I,J+NC1)=PHI2(I,J)
      DO 286 I=1,N
      DO 286 J=1,NC3
 286  PHINEW(I,J+NC1+NC2)=PHI3(I,J)
      NMODE=NC1+NC2+NC3
      IF(NR.GT.0) THEN
      DO 288 I=1,N
      DO 288 J=1,NR
 288  PHINEW(I,J+NMODE)=PHI4(I,J)
      NMODE=NMODE+NR
      ENDIF
      PRINT*,' THE REARRANGED PHI MATRIX IS'
      CALL PRNT(PHINEW,N,NMODE)
C
C
C  NEXT GENERATE THE [G1:G2:G3:G4] MATRIX
```

```
C  NEXT GENERATE THE [G1:G2:G3:G4] MATRIX
C
C
      DO 291 I=1,NSEN
      DO 291 J=1,NC12
  291 GPART(I,J)=GAIN1(I,J)
      DO 292 I=1,NSEN
      DO 292 J=1,NC22
  292 GPART(I,J+NC12)=GAIN2(I,J)
      DO 294 I=1,NSEN
      DO 294 J=1,NC32
  294 GPART(I,J+NC12+NC22)=GAIN3(I,J)
      NMOD2=NC12+NC22+NC32
      IF (NR.GT.0) THEN
      DO 296 I=1,NSEN
      DO 296 J=1,NR2
  296 GPART(I,J+NMOD2)=GAIN4(I,J)
      NMOD2=NMOD2+NR2
      ENDIF
C
      PRINT*,'THE G PARTITION MATRIX IS'
       DO 66 I=1,NSEN
   66  PRINT'(1X,12F10.5)',(GPART(I,J),J=1,12)
       PRINT'(//)'
       DO 67 I=1,NSEN
   67  PRINT'(1X,12F10.5)',(GPART(I,J),J=13,24)
       PRINT'(///)'
C
C
      CALL YHAT(CLOS,NSEN,NC1,NC2,NC3,NR,MM,XHAT,PETA,PXHT,CV,V
     &,NMOD2,PHINEW)
      PRINT*,' THE SCALING FACTOR IS ',SCALEB
      CALL VMULFF(GPART,PXHT,NSEN,NMOD2,MM,NSEN,NMOD2,UHAT,NSEN,IER)
      CALL TIME(EAT2,MM,DT,NACT,X0,X1,XHAT,UHAT,EAT,WORK,DUM6,
     &DUM2,DUM3)
      PRINT'(//)'
C
C
 300  CONTINUE
C
C
C  EIGENVALUE ANALYSIS SECTION
??
```

```
      SUBROUTINE TANGL(FIEA,N,NACT,PMAG,ANGL)
      REAL FIEA(N,NACT),ANGL(N,N),PMAG(N)
      REAL CDOT,MAGI,CANG
      INTEGER I,J,K,N,NACT
C
C  COMPUTE MAGNITUDE OF EACH VECTOR
      DO 2 I=1,N
      MAGI = 0.0
      DO 1 J=1,NACT
      MAGI = MAGI + (FIEA(I,J)**2)
    1 CONTINUE
      PMAG(I) = (MAGI**0.5)
    2 CONTINUE
C  COMPUTE DOT PRODUCTS
      DO 5 I=1,N
      DO 4 J=I,N
      CDOT = 0.0
      DO 3 K=1,NACT
      CDOT = CDOT + FIEA(I,K)*FIEA(J,K)
    3 CONTINUE
      ANGL(I,J)=CDOT
    4 CONTINUE
    5 CONTINUE
C  COMPUTE THE ANGLES
      DO 7 J=1,N
      DO 6 I=J,N
      CANG = ANGL(J,I)/(PMAG(I)*PMAG(J))
      IF(CANG.GT.1.0)THEN
      CANG = 1.0
      ENDIF
      ANGL(I,J)=ACOS(CANG)
      ANGL(I,J)=ANGL(I,J) * 57.295779514
      IF(ANGL(I,J).GT.90.)THEN
      ANGL(I,J) = ANGL(I,J) - 180.0
      ENDIF
    6 CONTINUE
    7 CONTINUE
C  PRINT ANGLE TABLE
      DO 9 J=1,N
      DO 8 I=J+1,N
      ANGL(J,I)=ANGL(I,J)
    8 CONTINUE
    9 CONTINUE
      PRINT'(/)'
      PRINT*,'      THE RELATIVE ANGLES BETWEEN THE MODES ARE'
      PRINT*,'        '
      PRINT*,' MODE      1          2          3          4          5
     &     7          8          9          10          11          12'
      DO 10 I=1,N
      PRINT'(1X,I4,12(2X,1F7.2))',I,(ANGL(I,J),J=1,N)
   10 CONTINUE
      PRINT'(/)'
      RETURN
      END
```

```
      SUBROUTINE YHAT(CLOS,NSEN,NC1,NC2,NC3,NR,MM,XHAT,PETA,PXHT,CV,V
     &,NMOD2,PHINEW)
      COMMON/MAINA/NDA,NDA1
      COMMON/MAINB/NCOL
      INTEGER L,LL,T,TT,K3
      INTEGER I,J,K,KK,MM,NSEN,NACT,NMODE,NMOD2
      REAL CV(2,NCOL),V(NCOL,NCOL),PETA(NCOL,NDA),PXHT(NMOD2,NDA)
      REAL XHAT(2,NDA),CLOS(2,NCOL),PHINEW(NCOL,NCOL)
      NMODE=NC1+NC2+NC3+NR
      CALL VMULFF(CLOS,PHINEW,2,NMODE,NMODE,2,NCOL,CV,2,IER)
      PRINT*,' THE CLOS * PHINEW PARTITION MATRIX IS '
      PRINT*,'          '
      DO 76 I=1,2
   76 PRINT'(1X,12F10.5)',(CV(I,J),J=1,12)
      PRINT'(//)'
C
C  GENERATE THE MATRIX P(ETA) TO EXTRACT ETA
C  FROM THE FULL STATE VECTOR Z
C
C
C  THE MATRIX PXHT EXTRACTS XHAT (ETAHAT:ETADOTHAT)
C  FROM THE FULL STATE VECTOR Z
C
      DO 60 I=1,NMODE
      DO 59 J=1,MM
      PXHT(I+NMODE,J)=0.0
      PXHT(I,J)=0.0
 59   PETA(I,J)=0.0
 60   CONTINUE
      L=2*NC1
      LL=L+NC1
      DO 61 I=1,NC1
      PETA(I,I)=1.0
      PXHT(I,I)=1.0
      PXHT(I,I+L)=1.0
      PXHT(I+NC1,I+NC1)=1.0
      PXHT(I+NC1,I+LL)=1.0
 61   CONTINUE
      K=NC1
      T=2*NC1
      KK=4*NC1
      K3=KK+NC2
      L=KK+2*NC2
      LL=L+NC2
      TT=T+NC2
      DO 62 I=1,NC2
      PETA(I+K,I+KK)=1.0
      PXHT(I+T,I+KK)=1.0
      PXHT(I+T,I+L)=1.0
      PXHT(I+TT,I+K3)=1.0
      PXHT(I+TT,I+LL)=1.0
 62   CONTINUE
```

```
      K=K+NC2
      T=T+2*NC2
      KK=KK+4*NC2
      K3=KK+NC3
      L=KK+2*NC3
      LL=L+NC3
      TT=T+NC3
      DO 63 I=1,NC3
      PETA(I+K,I+KK)=1.0
      PXHT(I+T,I+KK)=1.0
      PXHT(I+T,I+L)=1.0
      PXHT(I+TT,I+K3)=1.0
      PXHT(I+TT,I+LL)=1.0
63    CONTINUE
      IF (NR.EQ.0) GOTO 65
      K=K+NC3
      T=T+2*NC3
      KK=KK+4*NC3
      K3=KK+NR
      TT=T+NR
      L=KK+2*NR
      LL=L+NR
      DO 64 I=1,NR
      PETA(I+K,I+KK)=1.0
      PXHT(I+T,I+KK)=1.0
      PXHT(I+T,I+L)=1.0
      PXHT(I+TT,I+K3)=1.0
      PXHT(I+TT,I+LL)=1.0
64    CONTINUE
65    CONTINUE
      PRINT*,' THE MATRIX P(ETA) IS '
      PRINT'(/)'
      DO 66 I=1,NMODE
   66 PRINT'(1X,12F10.5)',(PETA(I,J),J=1,12)
      PRINT'(//)'
      DO 67 I=1,NMODE
   67 PRINT'(1X,12F10.5)',(PETA(I,J),J=13,24)
      PRINT'(//)'
      DO 68 I=1,NMODE
   68 PRINT'(1X,12F10.5)',(PETA(I,J),J=25,36)
      PRINT'(//)'
      DO 69 I=1,NMODE
   69 PRINT'(1X,12F10.5)',(PETA(I,J),J=37,48)
      PRINT'(////)'
      PRINT*,'THE MATRIX P(XHAT) IS'
```

```
      PRINT*,'THE MATRIX P(XHAT) IS'
      PRINT'(/)'
      DO 71 I=1,NMOD2
   71 PRINT'(1X,12F10.5)',(PXHT(I,J),J=1,12)
      PRINT'(//)'
      DO 72 I=1,NMOD2
   72 PRINT'(1X,12F10.5)',(PXHT(I,J),J=13,24)
      PRINT'(//)'
      DO 73 I=1,NMOD2
   73 PRINT'(1X,12F10.5)',(PXHT(I,J),J=25,36)
      PRINT'(//)'
      DO 74 I=1,NMOD2
   74 PRINT'(1X,12F10.5)',(PXHT(I,J),J=37,48)
      PRINT'(////)'
      CALL VMULFF(CV,PETA,2,NMODE,MM,2,NCOL,XHAT,2,IER)
      PRINT*,'XHAT'
      DO 75 I=1,48
      PRINT'(1X,2F10.6)',(XHAT(J,I),J=1,2)
   75 CONTINUE
C
C   XHAT = CLOS *  PHINEW * P(ETA)
C
C   UHAT = [G1:G2:G3:G4] * P(XHAT)
C
      RETURN
      END
```

```
      SUBROUTINE TIME(EAT2,MM,DT,NACT,X0,X1,XHAT,UHAT,EAT,WORK,
     &UBAR,TEFF,U1)
      COMMON/MAINA/NDA,NDA1
      COMMON/INOUT/KOUT
      REAL A,Z,EAT2(NDA,NDA),EAT(NDA,NDA),WORK(NDA,NDA)
      REAL DT,X0(NDA),X1(NDA),XHAT(2,NDA),XLOS(2),NEWCON
      REAL UBAR(NACT),TEFF(NACT),UHAT(NACT,NDA),U1(NACT)
      INTEGER I,J,K,M,KK,MM,NACT
      KK = 0
      DO 5 I=1,NACT
    5 TEFF(I)=0.0
      NEWCON=0.0
      A = 0.
      Z = DT * 1.
      PRINT*,'
     &           INTEGRATED EFFORT OF ACTUATOR AT TIME T'
      PRINT*,'
     &1           2           3           4           5           TOT'
      PRINT*,'  TIME       XLOS          YLOS         RADIUS
     &----------------------------------------------------------------'
      DO 10 I=1,MM
      DO 10 J=1,MM
 10   WORK(I,J) = EAT2(I,J)
      CALL VMULFF(XHAT,X0,2,48,1,2,48,XLOS,2,IER)
      CALL VMULFF(UHAT,X0,NACT,NDA,1,NACT,NDA,UBAR,NACT,IER)
      DO 6 I=1,NACT
    6 U1(I)=UBAR(I)
      RAD =((XLOS(1)**2) + (XLOS(2)**2))**0.5
      WRITE(*,15)A,XLOS(1),XLOS(2),RAD,TEFF(1),TEFF(2),TEFF(3),
     &TEFF(4),TEFF(5),NEWCON
 15   FORMAT(2X,1F5.3,3(2X,1F10.8),10X,5(1X,F10.8),1X,1F11.8)
 20   CONTINUE
      M = 0
 30   CONTINUE
      IF(KK.GT.0) THEN
      CALL VMULFF(WORK,EAT2,MM,MM,MM,NDA,NDA,EAT,NDA,IER)
      DO 40 I=1,MM
      DO 40 J=1,MM
      EAT2(I,J) = EAT(I,J)
 40   CONTINUE
      ENDIF
      KK = 1
      CALL VMULFF(EAT2,X0,MM,MM,1,NDA,NDA,X1,NDA,IER)
      DO 50 I=1,MM
 50   X0(I) = X1(I)
      NEWCON = 0.0
      CALL VMULFF(UHAT,X0,NACT,NDA,1,NACT,NDA,UBAR,NACT,IER)
      DO 55 I=1,NACT
      TEFF(I)=TEFF(I) + DT * ABS(UBAR(I) + U1(I))/2
      U1(I)=UBAR(I)
      NEWCON = NEWCON + TEFF(I)
   55 CONTINUE
```

```
      M = M + 1
      IF((M*DT).EQ.Z) THEN
      A = A + Z
      CALL VMULFF(XHAT,XO,2,NDA,1,2,NDA,XLOS,2,IER)
      RAD =((XLOS(1)**2) + (XLOS(2)**2))**0.5
      WRITE(*,15)A,XLOS(1),XLOS(2),RAD,TEFF(1),TEFF(2),TEFF(3),
     &TEFF(4),TEFF(5),NEWCON
      IF(A.GT.1.50) GOTO 60
      GOTO 20
      ELSE
      GOTO 30
      ENDIF
 60   CONTINUE
      RETURN
      END
```

??

```
      SUBROUTINE FORMPHI(FEE,PHI,N,NC,IC)
      COMMON/MAINB/NCOL
      REAL FEE(NCOL,NC),PHI(NCOL,NCOL)
      INTEGER IC(NC),M,N,NC,I,J
      DO 2 J=1,NC
      M = IC(J)
      DO 2 I=1,N
      FEE(I,J)= PHI(I,M)
 2    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE MMUL(X,Y,N1,N2,N3,Z)
      COMMON /MAINB/ NCOL
      DIMENSION X(NCOL,1),Y(NCOL,1),Z(NCOL,1)
      DO 3 J=1,N3
      DO 2 I=1,N1
      S=0.
      DO 1 K=1,N2
 1    S=S+X(I,K)*Y(K,J)
 2    Z(I,J)=S
 3    CONTINUE
      END
```

```
       SUBROUTINE PRNTSM(MAT,N,M)
       COMMON/MAINB/NCOL
       REAL MAT(2,NCOL)
       INTEGER I,J,K,L,M,N
       PRINT*,' '
       DO 1 L=1,M,12
       K = L + 11
       IF (M-L.LT.11) K = M
       DO 2 I=1,N
       PRINT'(1X,12F10.5)',(MAT(I,J),J=L,K)
 2     CONTINUE
       PRINT'(//)'
 1     CONTINUE
       PRINT'(///)'
       RETURN
       END
```

```
      SUBROUTINE PRNT(MAT,N,M)
      COMMON/MAINB/NCOL
      REAL MAT(NCOL,NCOL)
      INTEGER N,I,J,K,M
      PRINT*,' '
      IF (M.GT.12) GOTO 2
      DO 1 I=1,N
      PRINT'(1X,12F10.4)',(MAT(I,J),J=1,M)
1     CONTINUE
      GOTO 10
2     CONTINUE
      IF (M.GT.24) THEN
      CALL PRNTXL(MAT,N,M)
      RETURN
      ENDIF
      DO 3 I=1,N
      PRINT'(1X,12F10.4)',(MAT(I,J),J=1,12)
3     CONTINUE
      PRINT'(//)'
      DO 4 I=1,N
      PRINT'(1X,12F10.4)',(MAT(I,J),J=13,M)
4     CONTINUE
10    PRINT'(///)'
      RETURN
      END
```

```
      SUBROUTINE PRNTXL(MAT,N,M)
      COMMON/MAINB/NCOL
      COMMON/MAINA/NDA
      REAL MAT(NDA,NDA)
      INTEGER I,J,K,L,M,N
      PRINT*,' '
      DO 1 L=1,M,12
      K = L + 11
      IF (M-L.LT.11) K = M
      DO 2 I=1,N
      PRINT'(1X,12F10.5)',(MAT(I,J),J=L,K)
2     CONTINUE
      PRINT'(//)'
1     CONTINUE
      PRINT'(///)'
      RETURN
      END
```

```
1E0
3
4   4   4   0   6   6   0.005

-3.444180E-01      5.964265E-01      1.733589E-06
-3.106864E-02      5.378848E-02     -1.089512E-05
-5.079408E-02      6.517718E-02      6.379658E-02
-3.106498E-02      7.656002E-02     -6.378555E-02

-5.428713E-01     -3.135007E-01      1.990093E-01
-1.263367E-01     -7.294025E-02     -9.754515E-02
-1.097389E-01     -4.164450E-02      6.727962E-02
-9.092480E-02     -7.422176E-02      6.728645E-02

 4.921254E-02      2.843881E-02     -3.787724E-01
-3.124673E-01     -1.805243E-01     -6.518863E-02
-2.726674E-01     -1.274415E-01     -1.371115E-01
-2.465915E-01     -1.726473E-01     -1.371990E-01

 5.725899E-02     -9.915077E-02     -1.448014E-04
-1.759615E-01      3.045821E-01     -7.108848E-05
-2.387818E-01      3.408740E-01     -9.157857E-02
-1.759419E-01      3.771390E-01      9.148808E-02

 1.369714E-01      7.907730E-02      3.440897E-01
-1.620703E-01     -9.355460E-02      4.968926E-01
-1.620034E-01     -7.310584E-02      7.578209E-02
-1.443763E-01     -1.036703E-01      7.577509E-02

 2.975225E-05     -5.416100E-06      7.306890E-07
-2.041410E-01      3.535517E-01      5.599453E-06
-2.041407E-01     -3.535452E-01      1.247676E-04
 4.082401E-01      2.943104E-06     -2.833461E-05

 5.570818E-02     -9.646809E-02     -1.218230E-05
-3.438152E-02      5.957730E-02     -2.359900E-05
-2.880289E-02      5.645930E-02      4.873033E-01
-3.448512E-02      5.318449E-02     -4.871954E-01

-7.581691E-02     -4.378354E-02      1.837064E-01
 4.696140E-02      2.721564E-02      9.788533E-02
-3.677106E-02      3.243098E-02     -4.696553E-01
 4.650076E-02      1.559477E-02     -4.697591E-01
```

1.445489E-01	8.346642E-02	2.702091E-01
2.125086E-01	1.227663E-01	-3.266197E-01
-1.413814E-01	-3.096355E-01	-1.503790E-02
-3.389064E-01	3.227729E-02	-1.502664E-02

5.773717E-03	-9.966755E-03	5.299443E-05
2.242071E-01	-3.882475E-01	-4.343177E-05
-3.846467E-01	-3.681799E-02	1.180600E-02
2.241171E-01	3.147133E-01	-1.189199E-02

1.594218E-01	9.204970E-02	2.580694E-01
-1.516899E-01	-8.758898E-02	-3.116457E-01
-1.619330E-01	3.311046E-01	9.166399E-04
2.057674E-01	-3.057983E-01	9.186819E-04

8.373000E-02	4.834940E-02	1.586449E-01
-4.058438E-01	-2.343210E-01	-1.610843E-01
2.995810E-01	-1.419270E-01	-8.204982E-03
2.687799E-02	3.304098E-01	-8.208141E-03

0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.3536	-0.3536	0.0	0.0	0.0	0.0
-0.6124	0.6124	0.0	0.0	0.0	0.0
0.7071	0.7071	0.0	0.0	0.0	0.0
0.0	0.0	0.3536	-0.3536	0.0	0.0
0.0	0.0	0.6124	-0.6124	0.0	0.0
0.0	0.0	0.7071	0.7071	0.0	0.0
0.0	0.0	0.0	0.0	-0.7071	0.7071
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.7071	0.7071

0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.3536	-0.3536	0.0	0.0	0.0	0.0
-0.6124	0.6124	0.0	0.0	0.0	0.0
0.7071	0.7071	0.0	0.0	0.0	0.0
0.0	0.0	0.3536	-0.3536	0.0	0.0
0.0	0.0	0.6124	-0.6124	0.0	0.0
0.0	0.0	0.7071	0.7071	0.0	0.0
0.0	0.0	0.0	0.0	-0.7071	0.7071
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.7071	0.7071

```
   1.3420108
   1.6647234
   2.890712
   2.957132
   3.398200
   4.204482
   4.660268
   4.755260
   8.539417
  9.250564
  10.28478
  12.90511

2  3  8  9

5  6 11 12

1  4  7 10
0

-.001  .006  .001 -.009  .008 -.001 -.002  .002 .00   .00   .00 .00
-.003  .010  .030 -.020  .020 -.020 -.003  .004 .00 .00 .00 .00
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VITA

First Lieutenant Robert Glenn Baker was born on 29 September 1958 to Glenn H. and Ola M. Baker in Jacksonville, Florida. He graduated from Milton High School in Milton, Florida in 1976 and attended Auburn University from which he received the degree of Bachelor of Science in Applied Mathematics in December 1980. After graduation, he received a reserve commission in the United States Air Force through the Officer Training School in July 1981 where he was a distinguished graduate. He entered the School of Engineering, Air Force Institute of Technology, in August 1981 as his first assignment. In March 1983, he received the degree of Bachelor of Science in Aeronautical Engineering and accepted an extension of orders to enter the graduate program of the School of Engineering.

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Modern optimal control methods are used to develop a three controller system. The control problem is formulated in state vector form using full state feedback. The control is implemented on a modal representation of the structural equations of motion. State estimates are provided by a deterministic observer. A computer model is used to generate controller and estimator gains using steady state optimal regulator theory. Means for extracting structural response and control effort time histories are developed and related to the computer model.

The three controller system is used to control the CSDL I model subjected to physical initial conditions. This model is a lumped-mass tetrahedral truss consisting of four unit masses that are pin-connected by massless rods. Two versions of the model are used: the nominal version as designed by the Draper Lab and a perturbed version designed to minimize the deflection due to a static load.

Four structure/controller configurations are tested via computer simulations. Compatibility of modal groupings and the use/non-use of system triangularization are the factors varied to form the controller configurations. All configurations use three controllers each controlling four of the twelve modes. Modal input to the program is supplied by a NASTRAN analysis of each structure. Time histories of structural response and expended control effort are computed for each test configuration using a series of structural response weightings to vary the control and estimator gains. Performance curves are formed for each configuration to allow comparison of system efficiencies. The effect of the combination of modal compatibility and use/non-use of system triangularization on system effiency is examined. The relative "controllability" of the two structures is also discussed.

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